GENERAL SCIENCE

FOR TROPICAL SCHOOLS

BOOK III

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by

F. DANIEL

BOOK III

SECOND EDITION

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GENERAL SCIENCE FOR TROPICAL SCHOOLS

By F. DANIEL

A four-year course for secondary schools, especially written for use in tropical and sub-tropical areas. It consists of four books (I–IV), with an optional volume on Health Science (IIIA). There is also a Teacher's Handbook, which gives practical suggestions for the design and equipment of laboratories, lists of apparatus necessary for this General Science Course, and useful hints arising out of the author's experience in conducting it.

GENERAL SCIENCE WORKBOOKS

By A. ATKINSON *and* F. DANIEL

A graduated series of learning and testing exercises, in two books, designed to help the student to master the facts and principles presented in the General Science textbooks. Workbook I is for use with Books I and II of *General Science for Tropical Schools*; Workbook II is for use with Books III and IV.

HEALTH SCIENCE AND PHYSIOLOGY FOR TROPICAL SCHOOLS

By F. DANIEL

A self-contained textbook *designed primarily for students not following the author's General Science Course* and covering the syllabus in Health Science for the Cambridge Oversea School Certificate.

SUMMARIZED CONTENTS OF BOOKS I, II, III, IIIA, IV, AND TEACHER'S HANDBOOK

CONTENTS

BOOK THREE

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Borradaile: *Elementary Zoology for Medical Students*, fig. 86; Borradaile: *A Manual of Elementary Zoology*, figs. 103, 109 (both published by Oxford Medical Publications); *The Guide to the Refrigeration Exhibition*, issued by the Science Museum, Crown Copyright, by permission of The Controller of Her Majesty's Stationery Office, fig. 54; Osborn: *Origin and Evolution of Life* (Messrs. Charles Scribner's Sons, Ltd.), fig. 105; Thomson: *Biology of Birds* (Messrs. Sidgwick & Jackson, Ltd.), fig. 108; Messrs. William Watson & Sons, Ltd., figs. 169, 197; *Principles of Anatomy and Physiology for Physical Training Instructors*, by permission of The Controller of Her Majesty's Stationery Office, figs. 55, 71, 75; Bibby: *An Active Human Biology* (Messrs. William Heinemann, Ltd.), figs. 70, 73, 74; Grove and Newell: *Animal Biology* (University Tutorial Press), fig. 59.

PREFACE TO THE SECOND EDITION

During the fifteen years that have elapsed since these books were first published, General Science teaching has expanded rapidly, and half-a-million copies of these books have been used in oversea schools. During the same period there has been a steady improvement in the qualifications and experience of oversea science teachers, in school science equipment, and in the educational attainments (particularly in English) of oversea students following this General Science Course. At the same time, science itself has progressed; new scientific facts have emerged, and some of the older theories have been modified. Minor amendments were made in successive reprintings of the first edition, but more extensive revision had to await the preparation of this new edition. The original textbooks have had a far-reaching influence on science teaching in oversea schools, and it is hoped that this new edition will provide increasing numbers of oversea students with a better preparation for life in this scientific age.

F. DANIEL

Note.—The student should not part with this book. In studying Book IV he may want to refer back to the Glossary and to the Technical Terms listed in the Index.

In the text, the asterisk sign (*) is used to mark the first appearance of a general word that is not included in the standard vocabulary on which the Course is based (and which was not used in Books I or II). Such words are defined in the Glossary (pp. 305–311).

The dagger sign (†) marks the first appearance of a new scientific word or technical term that has not been used in Books I and II. Such words are also marked (†) in the Index so that the student

can refer back to where they were first used and explained in the text.

The *Teacher's Handbook* that accompanies this General Science Course is designed to help the teacher to use the textbooks to the best advantage.

CHAPTER I

HEAT

When you say that a fire gives out *heat*, and that you are *hot*, you may think that you know what you mean, but can you define the words *heat* and '*hotness*'?

A hot object weighs neither more nor less than the same object when it is cold, so heat is not a form of matter. It is a form of *energy*, like light, and it can be made to *do work*, as we shall see later. *Heat* is not the same thing as *temperature*, which is another word for 'hotness'. If one object is hotter than another, we say that it is *at a higher temperature*. Heat will flow from an object at a higher temperature to an object that is at a lower temperature, just as water flows from a higher to a lower *level*.

We can define *temperature* as *that condition of a body which decides whether it will give heat to, or receive heat from, other bodies*. The body that receives heat is at the lower temperature.

Heat a small iron nail until it is 'red hot', and heat a large piece of iron until it feels 'hot', but is not 'red hot'. Which is at the higher temperature?.................. Now take two large beakers and half fill each with tap-water. Dip your finger into each beaker in turn, and notice that both lots of water are equally warm to the touch. Now drop the red-hot iron nail into one beaker (A) and lower the large piece of hot iron into the other (B). Which lot of water becomes hotter, i.e. which is now at the higher temperature, A or B? ...... Which piece of iron has the greater 'temperature-raising power'? ....

The larger piece of hot iron had greater 'temperature-raising power' than the nail because, although it was at a *lower temperature* than the red-hot nail, it possessed a greater *quantity of heat*. The quantity of heat that a body possesses, and can give out, depends

not only upon its *temperature*, but also upon its *mass* and the *kind of material* in it.

HOW TEMPERATURE IS MEASURED

In the last experiment we used a very simple, but not very accurate, method of comparing temperatures. Up to the end of the sixteenth century, there were no special instruments for measuring temperature, and people depended on their sense of touch to test how hot an object was. But we cannot always depend on our *senses* for measurements of this kind, as the following experiment shows:

Take three large basins, the first containing ice-cold water, the second containing water that is just warm, and the third containing hot water (but not hot enough to scald your hand). Place your right hand in the hot water and your left hand in the cold water, and hold them there for at least a minute. Then quickly place both hands together in the just-warm water. You will find that it does not feel the same to both hands. Your right hand (which has been in the hot water) 'says' that the just-warm water 'feels cold', while your left hand (which has been in the cold water) 'says' that the just-warm water 'feels hot'. It is clear, therefore, that we cannot depend entirely on information that we get from the *sense-organs** in our skin about the 'hotness' of things. To overcome this difficulty, *thermometers* are used to measure temperature.

HOW THERMOMETERS ARE MADE

For most everyday purposes, we use *mercury thermometers*, which depend on the fact that when a liquid is heated its volume increases as its temperature rises and in proportion to the rise in temperature. The simplest kind of thermometer is made from a piece of thick-walled glass tubing with a very narrow bore (capillary tubing), which is blown out into a bulb at one end, as shown in Fig. 1. The tube is carefully selected with the bore of uniform diameter throughout its length. (Why?) The bulb is warmed so as to drive out some of the air, the open end of the tube is then

inverted in mercury and, as the bulb cools, some mercury enters the tube and bulb. This process is repeated until the bulb is full of mercury. The bulb and stem are now heated to a temperature slightly higher than that which the thermometer will ever have to measure, so that the mercury completely fills both bulb and tube. The upper (cup) end of the stem is then heated with a small blow-pipe flame and sealed. Usually a small 'safety bulb' is formed at the top of the stem (see Fig. 1). The thermometer is then stored away for some time, or 'aged', until the glass that has been heated has had time to contract to a permanent shape; this may take some weeks. It is then *graduated*, i.e. a scale of temperatures is marked on it. The bulb and the lower part of the stem contain mercury, while the space above the mercury in the stem is a vacuum (except in 'gas-filled' thermometers). When such a thermometer is warmed, the mercury expands and rises up the stem, while if the instrument is cooled the mercury contracts and falls in the stem. In this way we can get accurate information about temperature changes without depending upon our sense of touch.

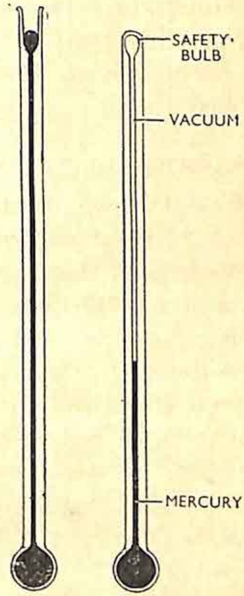

FIG. 1. Making a thermometer.

Mercury is the most suitable liquid for ordinary thermometers, for several reasons: (i) *It can be seen easily*, even in the very fine capillary tube of a thermometer stem; (ii) *It does not 'wet' glass*, hence, when the mercury contracts on cooling, no mercury is left behind up the stem sticking to the glass; (iii) *It is a good conductor of heat* (see p. 30) and soon reaches the same temperature as its surroundings; (iv) *It has only a small capacity* for heat*, i.e. only a little heat is required to raise its temperature (see p. 50); (v) *It does not boil or freeze readily*. (The 'boiling-point' of mercury is 357° C., and its 'freezing-point' is − 39° C.)

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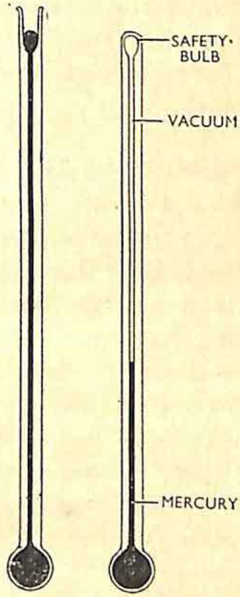

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HOW THERMOMETERS ARE GRADUATED—THERMOMETER SCALES

To be of use in comparing temperatures, thermometers must all be graduated on the same plan. The first step in graduating any thermometer is to mark on it *two standard temperatures*, or '*fixed points*'.

The lower fixed point is the temperature at which pure ice melts.

The higher fixed point is the temperature of steam from water boiling under normal atmospheric pressure (30 in. or 760 mm. of mercury).

The two fixed points are defined in this way because it is always easy to get pure ice, and pure steam from boiling water.

CENTIGRADE THERMOMETERS

For most scientific work, and for everyday purposes in some countries, the *Centigrade scale* is used. On this scale, the *lower fixed point* is called 0° *Centigrade* (0° C.), and the *higher fixed point* is called 100° *Centigrade* (100° C.). The interval between these two fixed points is divided into 100 equal parts called *Centigrade degrees.*

FAHRENHEIT THERMOMETERS

For everyday purposes in British and American countries the *Fahrenheit*† *scale* is used. On the Fahrenheit scale, the *lower fixed point* is called 32° *Fahrenheit* (32° F.), and the *higher fixed point* is called 212° *Fahrenheit* (212° F.). The interval between these two fixed points is divided into 180 equal parts called *Fahrenheit degrees*. Hence, 180 Fahrenheit degrees = 100 Centigrade degrees.

CONVERSION OF CENTIGRADE AND FAHRENHEIT SCALES OF TEMPERATURE

If you remember that the lower fixed point is 0° C. or 32° F., and that the higher fixed point is 100° C. or 212° F., it is easy to change Centigrade readings into Fahrenheit, and vice versa.

Example.—What is 30° C. on the Fahrenheit scale?

30° C. is 30 Centigrade degrees above the lower fixed point.

But 100 Centigrade degrees = 180 Fahrenheit degrees.

Therefore, 30° C. is $\frac{30 \times 180}{100}$ = 54 Fahrenheit degrees above the lower fixed point. But the lower fixed point is 32° F., therefore 30° C. is $54 + 32 = 86$° F.

Example.—What is 77° F. on the Centigrade scale?

77° F. is $77 - 32 = 45$ Fahrenheit degrees above the lower fixed point, $= \frac{45 \times 100}{180} = 25$ Centigrade degrees above the lower fixed point. But the lower fixed point is 0° C., therefore 77° F. $= 25 + 0 = 25$° C.

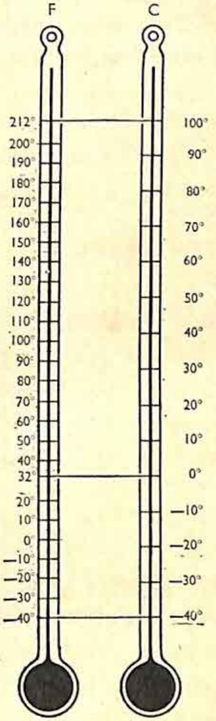

FIG. 2. Scales of temperature.

The quickest way to convert temperatures is by means of a graph. Draw a graph connecting the Centigrade and Fahrenheit scales of temperature, between — 40° C. and 200° C. From your graph, find at what temperature a Centigrade thermometer and a Fahrenheit thermometer both read the same number of degrees: ....

HOW TO TEST THE ACCURACY OF THE LOWER FIXED POINT OF A THERMOMETER

Fill a glass funnel with clean ice broken into small pieces. Place the bulb of a thermometer in the middle of the ice so that the lower fixed point is below the level of the ice. After ten minutes, raise the thermometer slightly so that you can see the surface of the mercury in the stem, as shown in Fig. 3, and take the reading. Push the thermometer down into the ice again, and take the reading again after a further five minutes. If this reading is the same as the first it can be taken as the lower fixed point.

Thermometer reading in melting ice = ...°. Error = ...°.

Add some salt to the ice in the funnel and take the reading of the same thermometer after five minutes.

Thermometer reading in ice and salt = ...°.

This shows the importance of using *pure ice* when marking the lower fixed point.

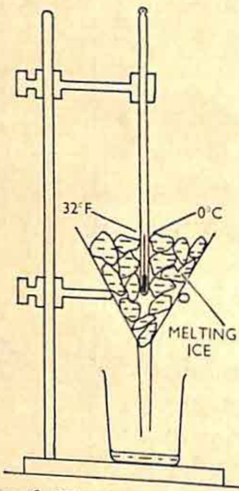

FIG. 3. The lower fixed point.

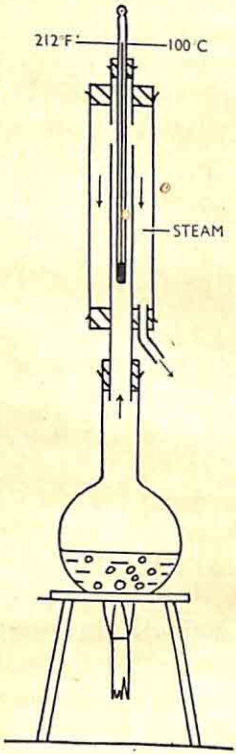

FIG. 4. The higher fixed point.

HOW TO TEST THE ACCURACY OF THE HIGHER FIXED POINT OF A THERMOMETER

Push a thermometer through the cork in the apparatus shown in Fig. 4, so that nearly the whole of the thermometer is surrounded

by steam which is issuing gently from the outlet tube. See that the bulb of the thermometer is well above the level of the boiling water, however, so that it is not splashed with drops of water. After the thermometer has been exposed to dry steam for ten minutes, take the reading. Keep the thermometer in the steam for a further five minutes and then take the reading again. If this second reading is the same as the first, it can be taken as the higher fixed point.

Thermometer reading in steam = ...°. Error = ...°.

Hold the bulb of the same thermometer in some boiling salt solution (10 per cent. sodium chloride).

Thermometer reading in boiling salt solution = ...°.

Wash the thermometer bulb (after cooling slowly) and then hold it in the *steam* from the boiling salt solution.

Thermometer reading in *steam* from boiling salt solution = ...°.

This shows the importance of marking the higher fixed point with the thermometer in *steam*, for although dissolved impurities raise the boiling-point of water, they make no difference to the temperature of the freely-escaping steam.

THERMOMETERS FOR SPECIAL PURPOSES—MAXIMUM THERMOMETERS

With an ordinary thermometer we can only measure the temperature at one particular time. For some purposes, however, it is necessary to know the highest temperature reached during a long period,* e.g. the highest temperature reached during a twenty-four hour day.

For this purpose a *maximum thermometer* is used, like the one shown in Fig. 5, which consists of a mercury thermometer with its stem in a horizontal position. A small glass, or steel, *indicator** is placed in the stem of the thermometer above the mercury surface. The mercury expands as the temperature rises and, since mercury does not 'wet' glass or steel, it pushes the indicator along in front of it. When the temperature falls and the mercury contracts, the indicator is left behind. In this way, the end of the indicator *nearer*

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This shows the importance of using *pure ice* when marking the lower fixed point.

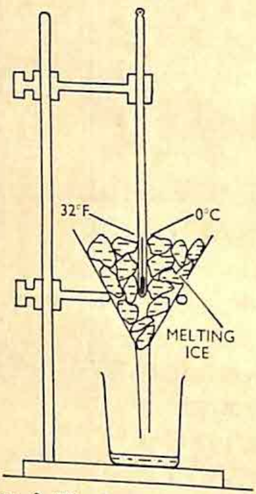
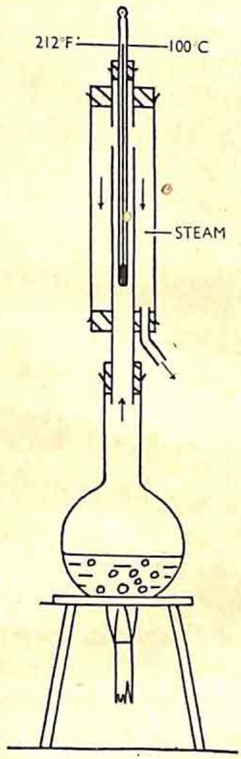


FIG. 3. The lower fixed point.



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the bulb marks the highest temperature reached. The indicator can be re-set in contact with the mercury surface by sloping the instrument; or, if the indicator is made of steel, by means of a magnet.

MINIMUM THERMOMETERS

When it is necessary to record the lowest temperature reached during a long period we use a *minimum* thermometer* that works in much the same way as the maximum thermometer we have just described, but which uses *alcohol* instead of mercury. One reason for using alcohol is that although mercury can be used in thermo-

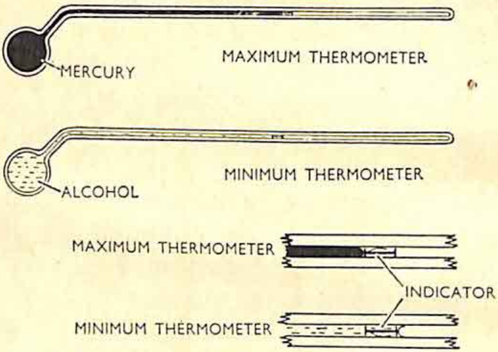


FIG. 5. Maximum and minimum thermometers.

meters for most everyday purposes, it freezes at $-39°$ C., so for very low temperatures alcohol is more suitable because it does not freeze until $-112°$ C. Its boiling-point, however, is also comparatively low (78° C.), so that an alcohol thermometer cannot be used for high temperatures.

In the minimum thermometer shown in Fig. 5, when the temperature rises the alcohol expands, 'wets' the indicator, and flows freely past it without moving it along. When the temperature falls and the alcohol contracts, the *surface tension* of the alcohol surface pulls the indicator back along the tube. Any later rise of temperature merely causes alcohol to flow freely past the indicator without disturbing its position. Hence, the end of the indicator *farther away*

from the bulb marks the lowest temperature reached. The indicator can be re-set by sloping the instrument or by using a magnet.

COMBINED MAXIMUM AND MINIMUM THERMOMETERS

Six's self-recording thermometer records both the highest and the lowest temperatures reached since the instrument was last set. As shown in Fig. 6, a narrow bent tube holding mercury between C and D joins a large bulb A to a smaller bulb B. A is filled with alcohol to C, and B is partly filled with alcohol above D. Above

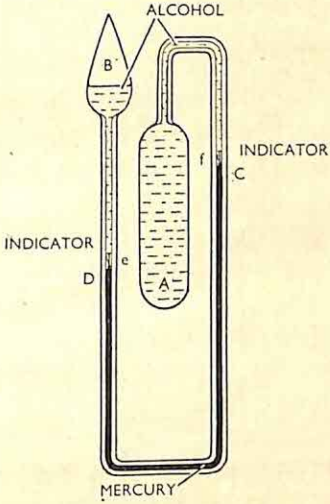


FIG. 6. Diagram of Six's self-recording thermometer.
(The actual tube is narrower than is here shown.)

the mercury at C and D are placed steel indicators *f* and *e*, fitted with small springs to stop them from slipping accidentally. As the temperature rises, the alcohol in A expands and pushes the thread of mercury before it, so that the *lower end* of the indicator *e* marks the highest temperature reached. The bulb B must not become full of liquid at any temperature for which the thermometer will be used, or it will break. As the temperature falls, the alcohol in A contracts and the mercury thread is drawn back towards A,

pushing before it the other indicator *f*, whose *lower end* marks the lowest temperature reached. By means of a magnet the instrument is re-set with both the indicators touching the mercury.

THE DOCTOR'S THERMOMETER

The normal temperature of a healthy person's blood is 98·4° F. (= *37° C.*), and by measuring any variations from this normal temperature a doctor can get valuable information about a patient's* health. If an ordinary thermometer were used, the instrument would have to be read while it was still in the patient's mouth or under his arm-pit, and this would be inconvenient. It is much better to use a special type of maximum thermometer that is graduated from 95° F. to 110° F. in fifths of a degree.

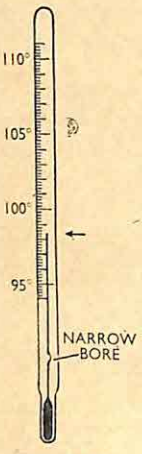


FIG. 7. The doctor's thermometer.

In the doctor's thermometer, the bore of the tube is very narrow at a point just above the bulb, as shown in Fig. 7. When the instrument is placed in the patient's mouth, the mercury expands, and its expansion pushes it through this narrow bore and up the stem. When the thermometer is removed from the mouth, the mercury in the bulb cools and contracts, but the mercury in the stem cannot return through the narrow bore by its own weight and so stays where it was when the thermometer was in the patient's mouth. A doctor's thermometer, therefore, can be taken out of the mouth and read in a good light. To re-set the instrument for a fresh observation, it is necessary to shake it sharply to make the mercury thread in the stem return through the narrow bore into the bulb. The glass stem of the thermometer usually acts as a lens that magnifies the very fine thread of mercury so that it is more easily seen.

Why is it wrong to clean a doctor's thermometer by washing it in boiling water?.......................................

In the same way that a *barograph* gives a continuous record of *pressure* changes (see Book II, Chap. IV), a *thermograph*† gives a continuous record of *temperature* changes. In one type of thermograph, a flattened metal tube, bent into a curve, is completely filled with liquid and then sealed up. When the temperature

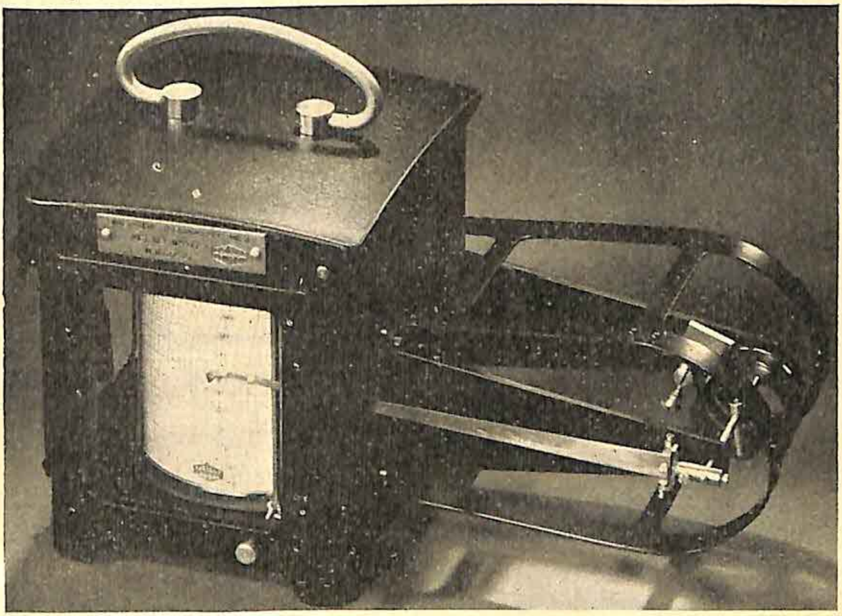


FIG. 8. A self-recording thermometer, or thermograph.

rises, the liquid expands and so straightens out the curved tube (this should remind you of the Bourdon Gauge). By a system of levers this movement is magnified and made to move a pen touching a sheet of squared paper fastened round a slowly revolving drum turned by clockwork; thus giving a continuous *graph* that records changes of temperature plotted* against time.

Another type of thermograph (shown in Fig. 8) makes use of a

spiral bi-metallic strip like the one shown in Fig. 18 and explained on p. 17.

EXPANSION AND ITS EFFECTS

Nearly all substances—solids, liquids, and gases—increase in size, or *expand*, when heated, and *contract* when cooled. With solids, expansion is so small that we generally have to use delicate instruments to measure it. Liquids, however, expand more than

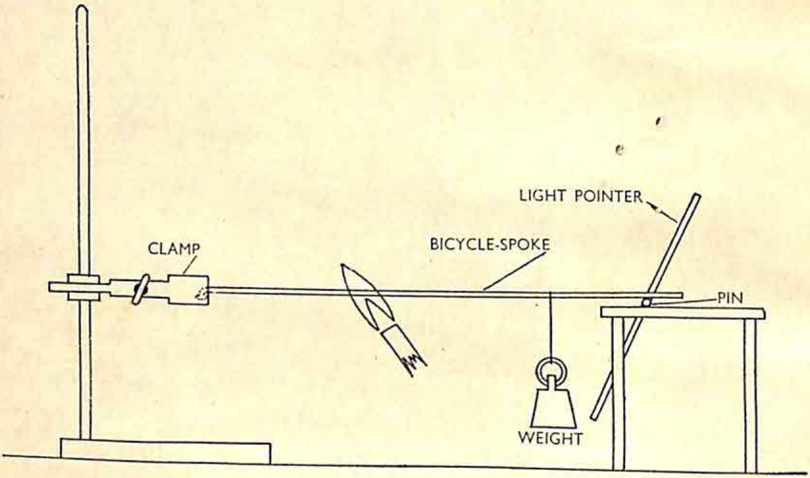


FIG. 9. Expansion of metal rod.

solids, while gases expand even more than liquids, for the same rise of temperature.

HOW TO SHOW THAT SOLIDS EXPAND WHEN HEATED

(i) Clamp the bent end of a bicycle-spoke* to a retort-stand and allow the other (screwed) end to rest on a pin carrying a long, light pointer (paper, wood, or drinking straw) as shown in Fig. 9. Hang a weight (e.g. a small retort-ring) near the screwed end of the metal rod and put the pointer in a vertical position. Heat the metal rod by moving a Bunsen flame from end to end.

What happens? . . . .

. . . .

Why? . . . .

. . . .

Remove the flame and allow the rod to cool.

What happens? . . . .

. . . .

Why? . . . .

. . . .

. . . .

(ii) (*Demonstration.*) A very striking way of showing the expansion of solids when heated is to take a long piece of the wire used in electric heaters (36 S.W.G. Nichrome), 10–15 feet long, stretch it tightly between two insulated* supports, and then pass a strong electric current through it. The wire becomes hot, expands in length, and hangs down loosely between the supports. When the current is turned off, the wire cools and contracts to its original length once more, taking up its original horizontal position. This experiment also illustrates what happens to telephone wires exposed to big changes of temperature.

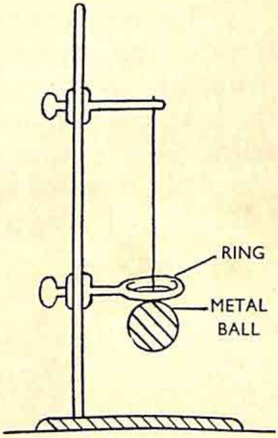


FIG. 10. Ball and ring.

(iii) The ball and ring experiment (Fig. 10) also illustrates the expansion of a solid. A metal ball, which just slips through a metal ring when it is cold, is heated. It is found that the heated ball will not fall through the unheated ring, showing that it has expanded. It slips through, however, after a few seconds, because the ring, too, gets hot and expands, becoming wide enough to let the ball fall through.

(iv) The bar and gauge experiment (Fig. 11) is another illustration of how solids expand when heated. An iron bar, which just fits inside the gauge when cool, is heated, and it is found that the

hot bar becomes too big to fit in the gauge owing to its expansion in length on heating. The round holes in the gauge are used to show that the bar also expands in thickness when heated.

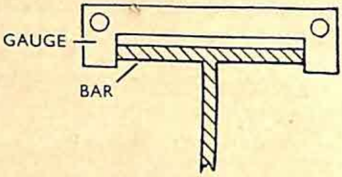


FIG. 11. Bar and gauge.

(v) The breaking bar experiment (Fig. 12) shows the enormous force of this expansion and contraction. A strong iron bar (of about 1 in. diameter) with a hole through one end and a screw at the other end, is mounted in a strong iron stand and heated with a burner. A short cast-iron* rod (of about $\frac{1}{4}$ in. diameter), or an old round file, is passed through the hole and the screw is tightened up until the rod presses tightly against the stop on the stand. The

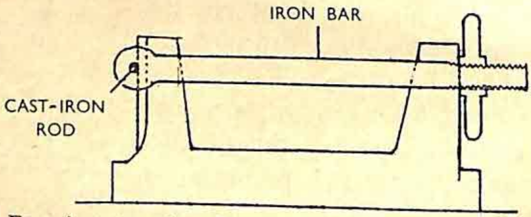


FIG. 12. Experiment to show force exerted in contraction on cooling.

strong iron bar is then allowed to cool, and, after a few minutes, the short cast-iron rod breaks owing to the enormous force of contraction. (Another arrangement of the same experiment shows that a similar force is produced during the expansion of the strong iron bar.)

EXAMPLES OF THE EXPANSION OF SOLIDS

Although solids expand and contract only slightly when heated and cooled, this small change in size often has to be taken into

account in everyday life. For example, a little space is left between the ends of railway lines so that they have room to expand on hot days (see Fig. 13).

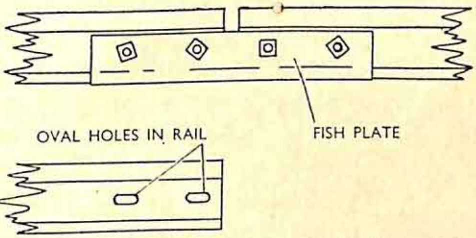


FIG. 13. Provision for expansion of railway lines.

Telephone wires expand slightly during the heat of the day and hang in a lower curve than in the cool of the night. If the wires are put up under hot conditions and stretched tight they will break when the temperature falls, making them contract in length.

Steel bridges, too, are slightly longer in hot weather than in cold, e.g. the Forth Bridge, in Scotland, is about 1 foot longer on a hot summer's day than on a cold day in winter. For this reason,

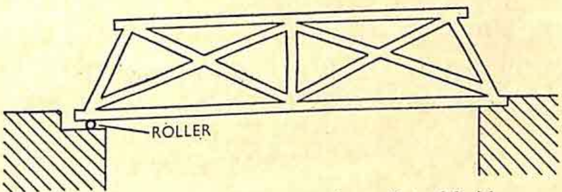


FIG. 14. Provision for expansion of steel bridge.

steel bridges are not fixed firmly at both ends, but slide on rollers (see Fig. 14).

Steam pipes are fitted with *expansion bends*, as shown in Fig. 15, to allow for expansion and contraction when the steam is turned on and off. Curved pieces of pipe are put in at intervals along the straight steam pipes, and these act as springs when there is any change in length.

Iron tyres for wooden cart-wheels are first made a little too small.

They are then heated red hot so that they expand sufficiently to slip over the wheel. On cooling, they contract and grip* the wheel very tightly. The steel tyres on railway engine wheels are put on in the same way. This is a very useful way to get a tight grip

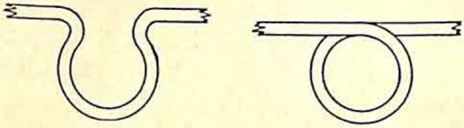


FIG. 15. Expansion bends in steam pipes.

between two pieces of metal. Thus ship-builders and boiler-makers use red-hot rivets†, and hammer them tight while still hot (see Fig. 16). Then, on cooling, the rivets contract and make a very firm joint. These are only a few of the everyday effects of *thermal* expansion.*

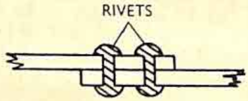


FIG. 16. A riveted joint.

COEFFICIENTS† OF EXPANSION

Although almost all solids expand on heating, different solids expand by different amounts. Brass, for example, expands more

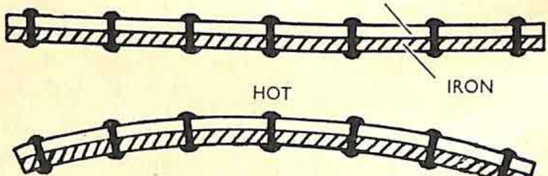


FIG. 17. Compound metal bar.

than iron under similar conditions. This can be shown by heating a bar consisting of two metal strips, one of brass and the other of iron, riveted together (see Figs. 17, 20). On heating, the bar bends

itself into a curve with the brass on the outside, since brass expands 50 per cent. more than iron under the same conditions. This bending of a compound metal bar is made use of in *bi-metallic* thermometers* (see Fig. 18).

In this Science Course we shall not concern ourselves with the accurate measurement of the expansion produced by rise of temperature, but the results of such measurements show that *the increase in length is proportional* (*a*) *to the original length, and* (*b*) *to the rise in temperature: Increase in length = original length × rise in temperature × a small fraction.*

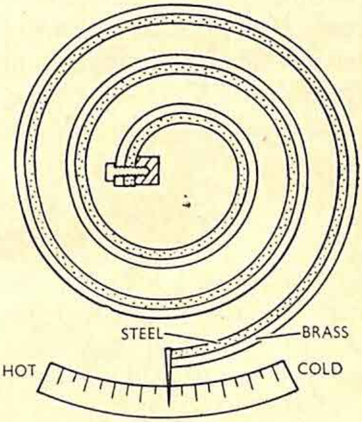


FIG. 18. Bi-metallic thermometer.

This small fraction (which is always the same for the same material) is called the '*coefficient of expansion in length*' of the solid.

The coefficient of expansion in length of a solid is the expansion of unit length (measured at 0° C.) when heated one degree Centigrade.

For solids, this coefficient of expansion in length is very small, only a few parts per *million*. For example, a brass rod that is exactly 1 metre long at 0° C. expands to 1·000019 m. when warmed to 1° C.; i.e. the coefficient of expansion in length of brass is 0·000019, or 19 parts per million.

The following values for coefficient of expansion in length show clearly the differences between the rates of expansion of some common solids: (The figures in brackets are *parts per million.*)

SODA GLASS	0·0000085 (8·5)	ALUMINIUM	0·000024 (24)
PYREX† GLASS	0·000003 (3)	BRASS	0·000019 (19)
FUSED QUARTZ	0·0000005 (0·5)	IRON	0·000012 (12)
PLATINUM	0·000009 (9)	INVAR†	0·0000009 (0·9)
COPPER	0·000017 (17)	ZINC	0·000028 (28)

You will notice that ordinary glass (soda glass) expands seventeen times as much as fused quartz for the same rise of temperature.

This explains why laboratory vessels made of fused quartz can withstand* rapid changes of temperature better than vessels made of ordinary glass. Similarly, *Pyrex glass* is very useful in the laboratory because its coefficient of expansion is only about one-third that of ordinary glass. Notice, also, that the rate of expansion of platinum is almost the same as that of ordinary glass. This explains why platinum wire can be fused to glass without cracking at the joint on cooling.

An actual example will show how coefficients of expansion are used in everyday problems. A single length of railway line is 66 ft. long. If the coefficient of expansion in length for iron is 0·000012, what is the difference in length when the air temperature changes from $-10°$ C. to 40° C. (i.e. 14° F. to 104° F.) [1]?

Increase in length = original length × rise in temperature × coefficient of expansion.

$$= 66 \times 50 \times 0{\cdot}000012 \text{ ft.}$$
$$= 0{\cdot}0396 \text{ ft.} = 0{\cdot}475 \text{ in.}$$

That is, if the lowest temperature to which the railway line is exposed is $-10°$ C. and the highest temperature is 40° C., a space of nearly half an inch must be left between the ends of the rails when they are at the lower temperature.

APPLICATION OF EXPANSION

The time of swing of a pendulum in a pendulum-clock depends on its length, and if the pendulum consists of a weight on the end of a long metal rod its length will vary with changes of temperature. Thus, when the temperature rises the pendulum will get longer and the clock will lose time, i.e. it will become 'slow'. In accurate clocks, therefore, the length of the pendulum must be kept always the same, and this is done by using some form of '*compensated* pendulum*'.

[1] In Siberia, the difference between day and night temperatures is sometimes even greater than this.

In the compensated pendulum shown in Fig. 19(*a*), the 'bob'† is supported at its centre by the outer steel tube. The top end of

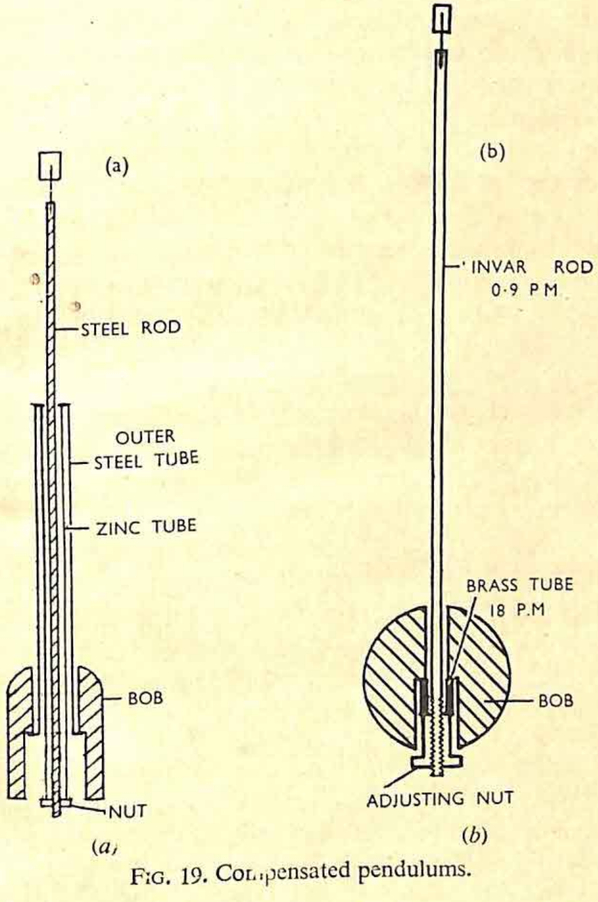


FIG. 19. Compensated pendulums.

this outer steel tube is supported by the zinc tube, the bottom end of which rests on the nut* at the bottom of the steel rod. Hence when the temperature rises, the inner steel rod and the outer steel tube expand *downwards* 12 parts per million for every rise of 1° C.,

while the zinc tube expands *upwards* 28 parts per million for every $1°$ C. By making the $\frac{\text{length of steel rod and tube}}{\text{length of zinc tube}} = \frac{28}{12}$, the length of the pendulum remains the same at any temperature. (Since the 'bob' is supported at its centre, the upward expansion of its top half is compensated by the downward expansion of its bottom half.) This type of compensated pendulum is used in tower-clocks with very long pendulums, e.g. Big Ben in the Houses of Parliament, London.

'INVAR' STEEL

In smaller pendulum-clocks the pendulum rod is made of a nickel steel called 'Invar', which has an exceedingly small coefficient of expansion (0·0000009), i.e. less than one part per million. ('Invar' is also used for making accurate measuring apparatus, e.g. surveyors' measuring tapes.*) In the arrangement shown in Fig. 19(*b*), the very slight downward expansion of the 'Invar' pendulum rod is compensated by the upward expansion of the short brass tube on which the 'bob' rests.

Since the expansion of brass is 20 times greater than the expansion of 'Invar' for the same rise of temperature, the brass tube is made one-twentieth the length of the 'Invar' rod. Notice also that the pendulum 'bob' is supported at its centre so that its own expansion makes no difference to the length of the pendulum.

COMPENSATED BALANCE WHEELS

The timing of a watch is controlled by the *balance wheel* that swings backwards and forwards under the action of the *hair-spring*. The time of swing depends on (*a*) the elasticity of the hair-spring, and (*b*) the radius of the balance wheel. When the temperature rises, the radius of the wheel increases by expansion, and the hair-spring becomes weaker, so that the watch 'loses' time. The expansion of the wheel could be avoided by making it of 'Invar', but this would not correct for the weakening of the hair-

spring. In order to overcome this difficulty, a *compensated balance wheel* can be used, as shown in Fig. 20, making use of the fact that brass expands more than iron.

The compensated balance wheel is made up of two curved segments,* each carried by a spoke. The segments consist of a strip of brass on the outside, joined to a strip of steel on the inside. When the temperature rises, the spokes expand and increase the radius of the wheel; but, at the same time, the two segments curve inwards and so compensate for the expansion of the spokes and also for the weakening of the hair-spring. In this way, the time of swing is kept always the same.

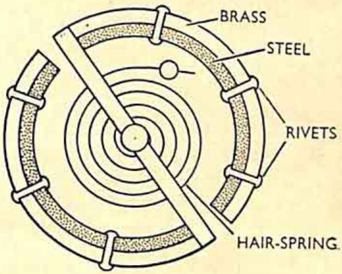


FIG. 20. Compensated balance wheel.

Nowadays, the hair-spring is usually made of a special nickel-steel (called 'Elinvar'†) whose elasticity does not change with temperature; and by combining this with an 'Invar' balance wheel it is possible to avoid the complications of the older type of compensated balance wheel, described above.

Before the invention of the compensated balance wheel (in 1757) there were no clocks sufficiently accurate for finding the longitude* at sea on long voyages. Nowadays, ships' officers do not depend so much on the accuracy of their clocks, since accurate wireless time-signals are sent out several times every day and any errors of ships' clocks can be corrected.

EXPANSION OF LIQUIDS

Since liquids have no shape of their own, but merely take the shape of the containing vessel, we are not concerned with the change of *length* but only with change of *volume*. In considering the expansion of liquids, however, it is to be remembered that liquids have to be put into containing vessels. On being heated,

the containing vessel expands as well as the liquid inside. In accurate work, therefore, we have to take into account this difference between the *real expansion* of the liquid itself and its *apparent* expansion* when the vessel containing the liquid also expands.

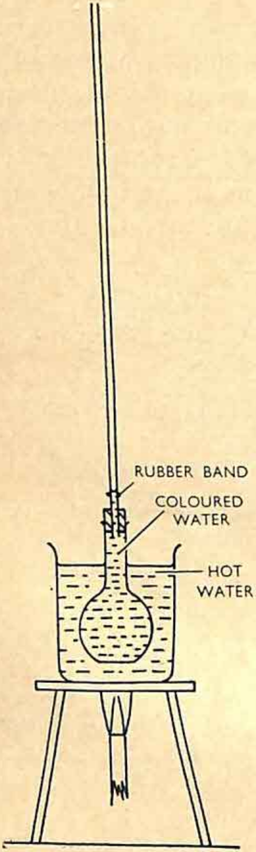


FIG. 21. Expansion of water.

HOW TO SHOW THE EXPANSION OF A LIQUID

Take a small flask fitted with a rubber cork carrying a long, narrow tube with its lower end just level with the bottom of the cork, as shown in Fig. 21. Fill the flask with coloured water and push in the cork. The water will rise a little way up the tube: mark the level with a rubber band. Place the flask in some hot water (in your water-bath).

What happens *immediately* the flask is placed in hot water? ....

....

....

....

Why? ....

....

....

What happens *for the next few minutes?*

....

....

Why? ....

....

....

Now put the flask into cold water.

What happens *immediately* the flask is put into cold water?

....

....

Why?..

....

THE EXPANSION OF WATER

Most liquids expand and contract uniformly for equal changes of temperature; this is why all the graduations on a mercury

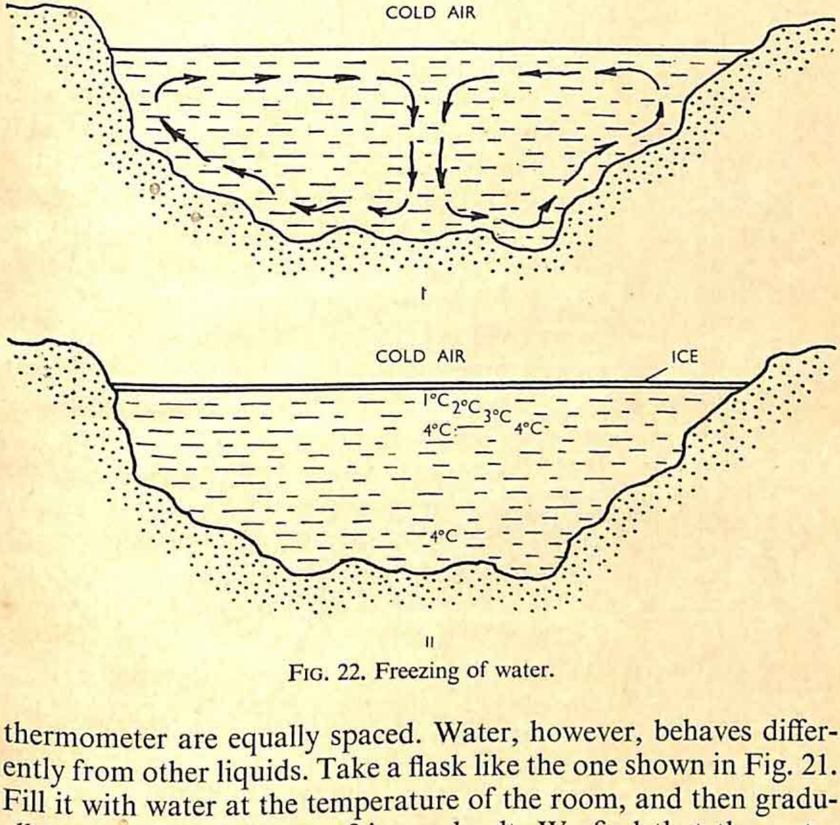


FIG. 22. Freezing of water.

thermometer are equally spaced. Water, however, behaves differently from other liquids. Take a flask like the one shown in Fig. 21. Fill it with water at the temperature of the room, and then gradually cool it in a mixture of ice and salt. We find that the water contracts *until its temperature reaches 4° C.* Then, on further cooling, *as the temperature falls from 4° C. to 0° C., the water expands*. In other words, *the density of water is greatest at 4° C.*,

and this temperature is called the *point of maximum density*. (This explains why the kilogram was originally defined as the mass of a litre of pure water *at 4° C.*)

This peculiar behaviour of water is very important in everyday life. Consider what happens in a quiet lake or pool when the temperature of the air above it falls below 0° C. The water near the surface will be cooled, and, as it contracts and becomes denser than the water below, it will sink. Warmer water will then rise to the surface to take its place. This will be cooled in turn and will then sink. In this way, all the water in the pond will *circulate* until it is cooled to 4° C., when this circulation will stop. Further surface cooling, however, causes the top layer of water to *expand*, so its density decreases and this cold water will remain at the surface, expanding still more until it freezes (see Fig. 22). The layer of *ice* that forms on the surface, being a bad conductor of heat, prevents further loss of heat from the water beneath, and practically all the unfrozen water will remain at 4° C. Hence in cold climates fishes and water-plants can live through the winter. If water contracted uniformly down to 0° C., lakes and pools would freeze *from the bottom upwards* instead of from the top, and the water would freeze to a solid mass of ice, killing nearly all the water animals and plants.

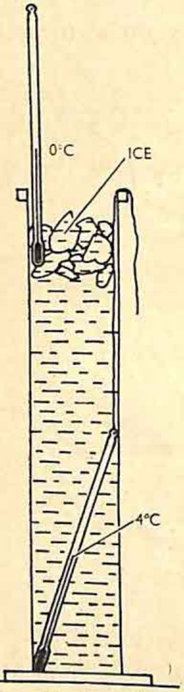


FIG. 23. Experiment showing temperature of maximum density of water.

This peculiar behaviour can be illustrated by the experiment shown in Fig. 23. The tall glass jar is nearly filled with water at about 10° C., and two thermometers, A and B, are put in the water, A with its bulb at the bottom of the jar and B with its bulb near the top. Crushed ice is then put in the jar and the two thermometers are read every minute. Both A and B cool down for some time,

until they both reach 4° C. Then A remains steady at about 4° C. while B goes on cooling until it reaches 0° C. (see also Fig. 22, ii).

THE EXPANSION OF GASES

When a gas is heated in a closed vessel, more *energy* is supplied to the *molecules*, making them move more rapidly and thus strike the walls of the containing vessel with greater force and frequency, i.e. the molecules tend to push the walls of the vessel outwards. In other words, the *pressure* increases. If the vessel is not closed, then the pressure will remain the same but the gas will *expand*. It is this expansion of gases with rise of temperature but without change of pressure that we shall now consider.

HOW TO SHOW THE EXPANSION OF A GAS

Use the flask and tube from your experiment to show the expansion of a liquid on p. 22. Empty out the water from the flask (thus filling it with air). Suck up a little coloured water into the tube, lay it horizontally on the bench and replace the flask, seeing that the drop of liquid is near the cork, as shown in Fig. 24. Then clamp the flask and tube in a vertical position and mark the level of the drop of liquid in the tube. Place your finger-tips on the flask.

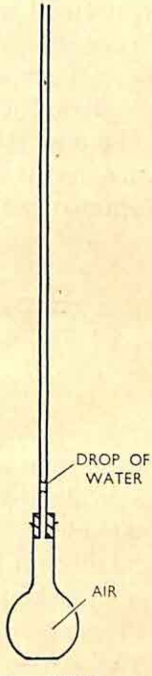


FIG. 24. Expansion of air.

What happens? ....
....

Why? ....
....

Then warm the flask between the palms of your hands, taking them away before the drop of liquid reaches the top of the tube.

What do your experiments tell you about the relative expansion of water and air? ....
....

CHARLES'S LAW—THE RELATION BETWEEN THE VOLUME AND THE TEMPERATURE OF A GAS

At the beginning of the nineteenth century, the French scientist Charles first showed the striking and simple fact that *all gases expand equally when heated*, i.e. *all gases have the same coefficient of expansion*. The influence of temperature on the volume of a gas is summed up in *Charles's Law—The volume of a gas increases by* $\frac{1}{273}$ *of its volume at 0° C. for every rise in temperature of 1° C., if the pressure on it is kept the same*. The coefficient of expansion for all gases, therefore, is $\frac{1}{273} = 0{\cdot}0037$ (or 3,700 parts per million).

To understand what this means, imagine some gas enclosed in a long, narrow tube by a drop of mercury, as shown in Fig. 25. Suppose that this tube is first placed in melting ice and the position

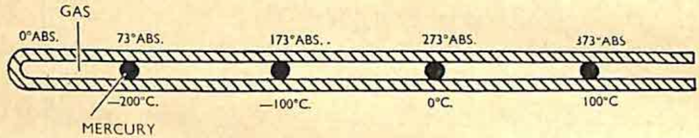


FIG. 25. Principle of gas thermometer.

of the mercury is marked. If the tube is then placed in steam, the gas will expand and the mercury will be pushed along towards the open end of the tube where its position can again be marked (the pressure on the enclosed gas being still one atmosphere). We have now marked the two *fixed points* on a *gas thermometer*.†

If we divide the interval between these two fixed points into 100 equal parts, we have a Centigrade thermometer. Now, if we go on marking off degrees of the same size *below* the lower fixed point until we reach the closed end of the tube, we shall find that the closed end reads $-273°$ C.

If we cool the tube below 0° C., the gas will contract $\frac{1}{273}$ of its original volume for every fall of 1° C.

Hence, in theory, on cooling to $-273°$ C. it will contract $\frac{1}{273} \times 273$ of its original volume, i.e. the volume of the gas will be reduced to nothing at $-273°$ C.

(In practice, all gases become liquid and then solid before reaching this temperature. Thus, hydrogen turns to a liquid at $-253°$ C. and solidifies at $-259°$ C.; helium liquefies at $-267°$ C. and solidifies at $-272°$ C.)

This temperature of $-273°$ C. is called the absolute zero† of temperature, and at this temperature a substance contains no heat*

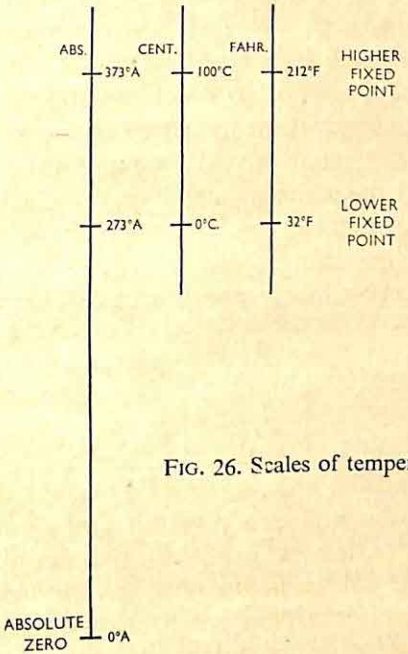


FIG. 26. Scales of temperature.

whatever. It is clear that nothing can ever be colder than this, because at this temperature a body has no more heat to lose. (A temperature of $-272{\cdot}995°$ C. ($= 0{\cdot}005°$ Absolute) was produced by a Dutch scientist in 1935.)

Readings on this new scale are called *Absolute temperatures.*† To convert Centigrade degrees into Absolute degrees we simply add on 273; e.g. $0°$ C. $= 273°$ Abs., $100°$ C. $= 373°$ Abs., and so on. The Absolute Scale of Temperature is a very useful scale for

scientific work because *the volume of a gas is directly proportional to its absolute temperature*, if the pressure remains the same. (This is another way of stating Charles's Law.) The subject of the expansion of gases, therefore, is much simpler than that of solids and liquids because *all gases expand equally when heated the same amount*, while every solid and liquid has its own individual coefficient of expansion.

HOW IS CHARLES'S LAW USED?

Charles's Law enables us to calculate the volume that a gas would occupy at a different temperature, e.g. a gas occupies 100 c.cm. at 10° C.; what would its volume be at 30° C. if the pressure remained the same?

Since the volume of a gas is proportional to its Absolute temperature, the first thing to do is to convert these Centigrade temperatures into Absolute temperatures, 10° C. = 283° Abs., and 30° C. = 303° Abs.

$$\text{Therefore, new volume at } 30^\circ \text{ C.} = \frac{100 \times 303}{283} = 107 \text{ c.cm.}$$

WHAT IS THE COMBINED EFFECT OF TEMPERATURE AND PRESSURE ON THE VOLUME OF A GAS?

According to Boyle's Law, *the volume of a gas is inversely proportional to the pressure*, and according to Charles's Law *the volume of a gas is directly proportional to the Absolute temperature.* We are now able to calculate the change in volume of a gas when both temperature and pressure are changed at the same time.

Boyle's Law can be written $P_1V_1 = P_2V_2$, and Charles's Law can be written, $\frac{V_1}{V_2} = \frac{T_1}{T_2}$, where T_1 and T_2 are Absolute temperatures.

It can be shown from these two laws that $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$ (*the Gas Equation*)†, where T_1 and T_2 are Absolute temperatures and where P_1, V_1, and T_1 represent the pressure, volume, and tem-

perature under one set of conditions, and where P_2, V_2, and T_2 represent the pressure, volume, and temperature under another set of conditions.

This *gas equation* is very useful in chemistry, where it is often necessary to find what volume a gas will occupy under *standard conditions of temperature and pressure*. For this purpose, *standard temperature* (or normal temperature) is 0° C. (273° Absolute), and *standard pressure* (or normal pressure) is 760 mm. of mercury.

Example—

A gas occupies 345 c.cm. at 27° C. (i.e. 300° Abs.) and a pressure of 750 mm. of mercury. What will be its volume at standard temperature and pressure?

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

Therefore, $$\frac{750 \times 345}{300} = \frac{760 \times V_2}{273}$$

Therefore, new volume $(V_2) = \dfrac{750 \times 345 \times 273}{300 \times 760}$

$$= 310 \text{ c.cm.}$$

THE MOVEMENT OF HEAT

HOW HEAT TRAVELS FROM PLACE TO PLACE

If one end of a short iron bar is heated in a Bunsen flame, the other end of the bar soon becomes warm also. The process by which heat travels along *through* the metal bar is called *conduction.*†

If the hot iron bar is removed from the flame and one hand is held about a foot *above* the hot end of the bar, the hot air rising from the heated iron carries heat upwards to the hand. This process, in which heat is conveyed* by moving air, is called *convection.*†

If the hand is held about a foot *below* the hot end of the iron bar

after it has been removed from the flame, the hand still receives some heat, though not so much as when it was held above the hot iron. This heat cannot have been conveyed by *convection*, because hot air rises, or by *conduction*, because air hardly conducts heat at all. This third process, by which heat travels independently of conduction and convection, is called *radiation*.†

We can say, therefore, that *heat may travel from one place to another in three different ways,*

(*i*) *By conduction, when heat travels through matter,*

(*ii*) *By convection, when heat is conveyed by moving fluid matter,*

(*iii*) *By radiation, when heat travels quite independently of matter.*

We shall now consider in more detail these three methods by which heat travels from place to place.

THE CONDUCTION OF HEAT

If we take two rods of the same size, one of copper and the other of glass, and hold one end of each in a flame, it is found that the other end of the copper rod soon becomes too hot to hold, while the other end of the glass rod remains quite cool. This is because copper *conducts* heat better than glass. Substances like copper, which allow heat to pass through them readily, are called *good conductors of heat*, while substances like glass, which do not allow heat to travel through them readily, are called *bad conductors of heat*. As a general rule, *metals are good conductors, and non-metals are bad conductors of heat.*

During conduction, the molecules in the heated part of the material receive heat-energy and vibrate more vigorously, passing on some of their heat-energy to cooler neighbouring molecules, so that, in time, heat is passed from molecule to molecule throughout the material.

GOOD CONDUCTORS

The metal that conducts heat best of all is *silver*. *Copper* is the next best conductor, then aluminium, brass, zinc, tin, iron, and lead, in that order. We can show the different conducting powers of

various materials by taking a metal can with holes in its bottom fitted with corks carrying rods of different materials, as shown in Fig. 27. Each rod is coated with paraffin wax and a wire indicator is embedded* in the wax at the top of each rod. The vessel is then filled with boiling water. The rods conduct heat from the hot water, and wax is melted along each rod, allowing the indicator to slide downwards. The order in which the indicators slide down the rods shows the order of their heat-conducting power.

In this experiment we used rods of........................

....

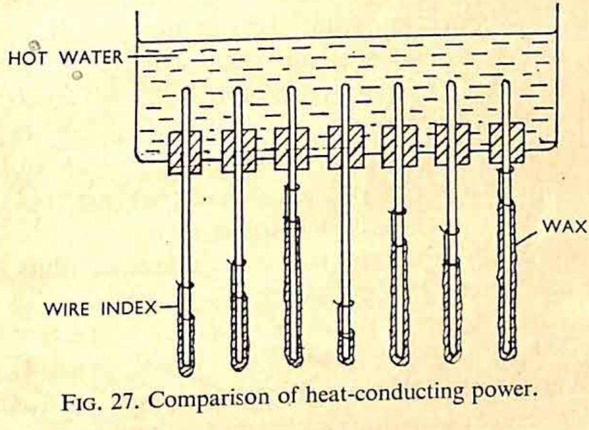


FIG. 27. Comparison of heat-conducting power.

and the order of their *heat-conducting power* (*or thermal conductivity*†) was as follows (best conductor first): ....

....

BAD CONDUCTORS

The poorest conductor of heat is, of course, nothing at all, i.e. a vacuum. Glass, wood, cork, cotton-wool, asbestos, rubber, ice, and still air are a few common substances that are bad conductors of heat.

All liquids (except mercury and other melted metals) are bad conductors of heat. If a piece of ice is wrapped in wire gauze or

weighted with lead so that it will sink in a test-tube of water, as shown in Fig. 28, the water can be boiled at the top of the tube without heating the water below, and the ice remains unmelted at the bottom of the test-tube. (N.B.—When a liquid is heated *from below*, heat is conveyed by *convection*, but when it is heated *from above* there is no circulation of the water and convection cannot take place.)

The heat-conducting power of copper is about 700 times greater than that of water, and the heat-conducting power of water is about 25 times greater than that of air. *All gases are very bad conductors of heat*, even worse than liquids, but it is very difficult to stop convection currents in a gas. It is sometimes possible to enclose air in porous materials like fur, feathers, cotton-wool, asbestos-wool, glass-wool, sawdust, and woven materials, thus stopping convection movements. Woven clothing materials owe their low conducting-power to the air they enclose in their pores.

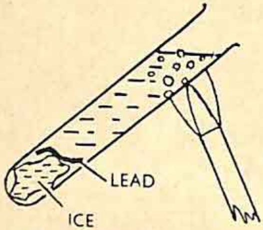


FIG. 28. Water boiling above ice.

EVERYDAY EXAMPLES OF THE USE OF GOOD AND BAD CONDUCTORS

Copper, being a very good conductor of heat, is often used for making cooking-vessels, for small boilers, and for boiler-tubes. Aluminium is used for motor-car crank†-cases and sometimes for pistons, partly on account of its light weight, but also because it is a much better conductor of heat than iron or steel.

The *miner's safety-lamp*, invented by Sir Humphry Davy in 1815, makes use of the high conducting-power of metals. The wire gauze surrounding the flame conducts away the heat so rapidly that any explosive gas outside does not get hot enough to catch fire. We shall learn more about the Davy lamp in later lessons (see Book Four, Chap. III.)

Ice-boxes and *refrigerators* are made with double walls having an air-space in between. This space is usually packed loosely with

grains of charcoal, cork, or some other porous material to stop convection movements in the air between the double walls.

We also make use of the non-conducting power of air when we wrap up a block of ice in cloth, or cover it with sawdust, to stop it melting too quickly. It is the air-spaces in the cloth or sacking, or between the grains of sawdust, that prevent heat from reaching the ice inside the porous covering.

THE CONVECTION OF HEAT

Convection can only take place in fluids (liquids and gases) since the molecules of a solid cannot travel about and thus convey heat (for their *vibration* does not change their relative position in the solid). When a fluid is heated from below, the heated part expands and its density becomes less, hence the heated part rises and colder fluid takes its place, thus becoming heated in turn. In this way a circulation is set up and the whole of the fluid becomes hotter. These movements can be illustrated by putting a small grain of a soluble dye at the bottom of a large beaker of water and then heating gently over a small flame. *Convection currents* are set up and the water circulates as shown in Fig. 29.

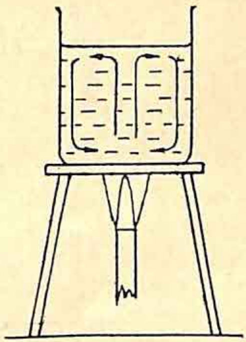


FIG. 29. Convection currents in water.

EVERYDAY EXAMPLES OF CONVECTION CURRENTS

The rise of smoke in a chimney is caused by convection currents: the hot air from the fire rises up the chimney, thus drawing in cold air at the bottom. In cold countries, this process helps to ventilate rooms.

Rooms can also be ventilated by means of convection currents without using a fire. Openings are left near the top of the room so that the warm, damp, expired air, which is less dense than the

fresh air, can escape, while cooler, drier, and denser fresh air enters through openings lower down in the walls.

Winds are convection currents produced in the atmosphere by the unequal heating of the Earth's surface by the Sun. Where one place on the Earth's surface is hotter than another, there is an upward current of air over the hotter place, a downward current over the cooler place, and a wind blows along the Earth's surface from the cooler region to the warmer region, e.g. Trade Winds.

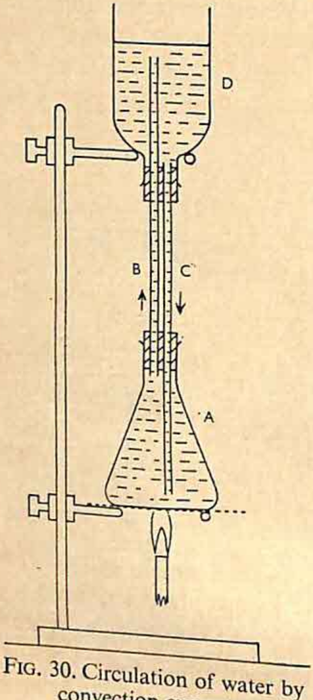


FIG. 30. Circulation of water by convection currents.

Land breezes and sea breezes are produced in a similar way owing to the different *heat-capacities* of earth and water. The land warms up more rapidly and also cools down more rapidly than the sea, producing corresponding changes in the air above. Hence, during the day, the air over the land becomes hotter than that over the sea; it expands, becomes less dense, and so rises. Cooler and denser air from over the sea then flows in to take its place, producing a *sea breeze*. At night, the land loses heat more rapidly than the sea, so that the air over the land becomes cooler and denser than that over the warmer sea, and a *land breeze* results.

Ocean currents, also, are largely convection currents.

In some laboratory 'fume cupboards', a lighted burner is placed below the chimney so that the heated air rises and sets up a convection current, carrying the chemical fumes along with it.

In cold countries, buildings are often heated by means of hot-water pipes. The apparatus shown in Fig. 30 illustrates the principle of hot-water heating. The upper vessel D is nearly filled with

coloured water, and a small flame is then placed under the lower vessel A, containing clean water. The movement of the coloured water shows that water circulates upward through tube B and downward through tube C. In houses that are arranged for hot-water heating, the water is heated in a boiler placed as low down as possible in the house. As the water expands and becomes less dense, it rises and circulates through pipes and 'radiators' in the various rooms until it cools and returns to the bottom of the boiler. There it is again heated, thus maintaining a steady circulation.

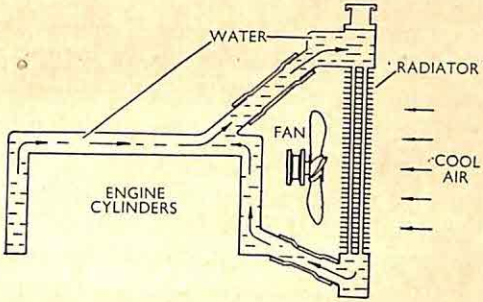


FIG. 31. The motor-car 'radiator'.

Heat can be conveyed from the cylinders of a motor-car to the atmosphere by using convection currents to circulate the cooling water through the water-space around the cylinders (the 'water jacket')* and then through the 'radiator' (see Fig. 31). The water in contact with the hot cylinders gets hot, expands, becomes less dense, and then rises to the upper part of the 'radiator' where it enters narrow tubes cooled by a current of air. In these tubes the water cools, contracts, becomes denser, and so sinks to the bottom of the 'radiator' and back into the 'water jacket' around the cylinders. (You will notice that a motor-car 'radiator' should really have been called a 'convector' since it conveys heat by convection and not by radiation.)

THE RADIATION OF HEAT

The third process by which heat is transferred—by *radiation*—is quite different from conduction and convection. Light and radiant heat are believed to travel in *transverse waves* like the water-waves that we studied in Book Two, Chap. VII, but with this very important difference: water-waves can only travel *through matter*, while light-waves and heat-waves can travel through a vacuum, i.e. *independently of matter*. Wireless waves and X-rays† are other forms of radiation travelling in the same way and with the same speed, differing from one another only in '*wave-length*'† (i.e. speed ÷ frequency).

We know that *radiant heat* and *light* both travel in the same way, for if we stand in the sunlight we can both see the Sun and feel its heat, but if we stand in the shade, we can neither see the Sun nor feel its heat; i.e. a light-shadow is also a radiant-heat-shadow.

The Sun warms the Earth by *radiation*, from a distance of about 93 million miles; and since radiant heat from the Sun arrives at the same time as its light, both must travel at the same speed. This is shown (see Fig. 113) clearly during an eclipse† of the Sun, when the light and the heat of the Sun are cut off at the same time. The Earth's atmosphere extends upwards for about 100 miles, and the greater part of the remaining space between Earth and Sun contains no material substance, i.e. it is a vacuum; hence *radiant heat travels independently of matter*.

Another difference between radiation and conduction or convection is that while conduction and convection are relatively slow processes of heat-movement, radiant heat travels with the enormous speed of light, i.e. 186,000 miles per second.

RADIATION AND ABSORPTION

Any hot object gives out radiant heat, and any cold object absorbs it; but the rate at which radiation and absorption take place depends largely on the nature of the *surface* of the objects. The following experiments illustrate this:

(i) Take two sheets of tin-plate (about 4 in. square), one brightly

polished and the other coated with soot (from an oil lamp), and fasten a cork to the back of each plate with a little paraffin-wax (see Fig. 32). Then hold the plates, one in each hand, by the corks, so that they face the Sun.

What happens?...

....

Why?...

....

(ii) Take two metal cans of the same size (e.g. cigarette tins), one with its outside surface brightly polished and the other one with its

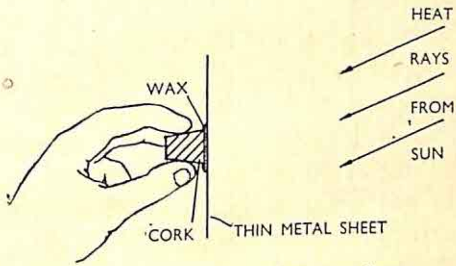


FIG. 32. Absorption of radiant heat.

outer surface coated with soot or lamp-black. Cut a hole in each lid and fit corks carrying thermometers. Place both tins on an asbestos sheet, pour the same quantity of nearly-boiling water into each, and then replace the lids and thermometers. Read the two thermometers every minute for the next ten minutes and record your readings on p. 38. Then construct two *cooling-curves* on graph-paper.

The blackened vessel cools faster than the polished one, showing that a dull-black surface radiates heat better than a brightly polished surface. Below 100° C., however, the heat lost by radiation is very small compared with the heat lost by convection, but radiation becomes much more rapid at higher temperatures, e.g. if we double the Absolute temperature of a surface it gives out 16 times (not twice) its previous amount of radiation.

(iii) Empty the water from both cans and repeat the experiment

with the two empty cans placed the same distance from a cylinder of wire gauze heated red hot by a Bunsen burner, as shown in

TIME	TEMPERATURE Black	Polished	TIME	TEMPERATURE Black	Polished
Start	°C.	°C.	6 min.	°C.	°C.
1 min.	°C.	°C.	7 ,,	°C.	°C.
2 ,,	°C.	°C.	8 ,,	°C.	°C.
3 ,,	°C.	°C.	9 ,,	°C.	°C.
4 ,,	°C.	°C.	10 ,,	°C.	°C.
5 ,,	°C.	°C.			

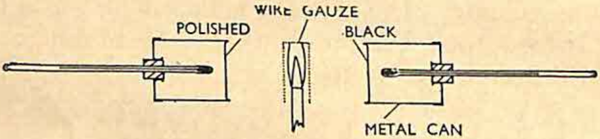


FIG. 33. Radiation and absorption.

Fig. 33. Read the two thermometers every minute for the next ten minutes and record your readings below. Then illustrate your results with two *absorption-curves* on graph-paper.

TIME	TEMPERATURE Black	Polished	TIME	TEMPERATURE Black	Polished
Start	°C.	°C.	6 min.	°C.	°C.
1 min.	°C.	°C.	7 ,,	°C.	°C.
2 ,,	°C.	°C.	8 ,,	°C.	°C.
3 ,,	°C.	°C.	9 ,,	°C.	°C.
4 ,,	°C.	°C.	10 ,,	°C.	°C.
5 ,,	°C.	°C.			

Experiment (ii) shows that *a dull-black surface is a good radiator of heat*, while *a polished surface radiates less heat*. Experiments (i) and (iii) show that *a dull-black surface is a good absorber of heat*, while *a polished surface absorbs heat less readily*. In other words, *good radiators are also good absorbers of heat*.

For this reason, in countries where the Sun's heat is very strong, people wear white clothes and a white sun-helmet;* these *reflect* most of the heat-rays. Similarly, whitewashed buildings absorb less heat than buildings with dark-coloured walls. Oil storage tanks, and balloons, are usually painted with aluminium paint so as to absorb as little radiant heat from the Sun as possible. A layer of polished aluminium foil* in a sun-helmet or in a roof reduces heat-transmission in the same way.

Notice that, since heat-*loss* by radiation is unimportant below 100° C., the colour of one's clothing makes no practical difference to heat-*loss* from the body, but it makes a lot of difference to the amount of heat *absorbed* in strong sunlight.

THE VACUUM FLASK

We have seen that heat can only travel from one place to another either by *conduction*, *convection*, or *radiation*. Hence, if we want to stop a substance from gaining or losing heat, we must stop these three processes. The *vacuum flask* (or Thermos flask) invented by Sir James Dewar about 1892, is a very efficient device for this purpose (see Fig. 34). It is a double-walled glass vessel, and the air between the inner and the outer walls is removed before the vessel is sealed. This vacuum stops the movement of heat by *conduction* and *convection*, owing to the absence of any matter to carry the heat. In order to stop *radiation* the glass surfaces between the inner and outer vessels are silvered.

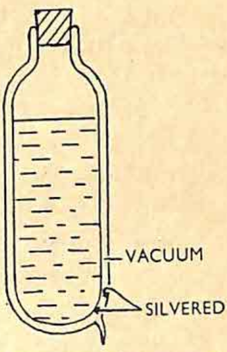


FIG. 34. The vacuum flask.

In this way it is just as difficult for heat to travel outwards as

inwards, and practically the only way in which heat can enter or leave the vessel is through the cork, which is itself a bad conductor of heat.

ICE, WATER, AND STEAM

WHAT IS THE CHANGE IN VOLUME WHEN WATER FREEZES?

We have seen (on pp. 23–24) that when water cools from 4° C. to 0° C. it expands very slightly. When water at 0° C. freezes to ice at 0° C., there is a much greater expansion (about one-eleventh), 11 c.cm. of water becoming about 12 c.cm. of ice. Most other liquids *contract* when they solidify.

As a result of this expansion on freezing, the specific gravity of

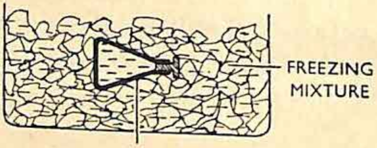


FIG. 35. Expansion on freezing.

ice is about 0·9, hence ice floats in fresh water with about nine-tenths of its volume below the surface of the water. In cold countries, ponds, lakes, and seas freeze only at the surface, and water plants and animals continue to live in the liquid water below the ice.

Another result of the expansion of water on freezing is that a very great force is exerted when ice is being formed and, in cold countries, metal water-pipes are often split open in winter. To show the great force exerted by the expansion of water on freezing, a small cast-iron bottle is filled with water and closed tightly with a screw stopper. The bottle is placed in a freezing-mixture of ice and salt, as shown in Fig. 35. After a time, the water freezes, expands, and bursts the iron vessel. Rocks at high altitudes and in cold countries are also broken up by the freezing of water in the

cracks of the rocks. The expansion of this water, as it freezes, splits off pieces of rock. This is one form of *weathering*.

WHAT IS THE EFFECT OF PRESSURE ON THE MELTING-POINT OF ICE?

The melting-point of ice (or the freezing-point of water) *is lowered by increased pressure*.

This lowering of the freezing-point can be illustrated by hanging two weights by a *thin* wire over a block of ice as shown in Fig. 36. The wire gradually cuts through the block, but leaves the ice solid behind it. This is because ice melts along the line of contact just below the wire, owing to the great pressure, and the wire sinks

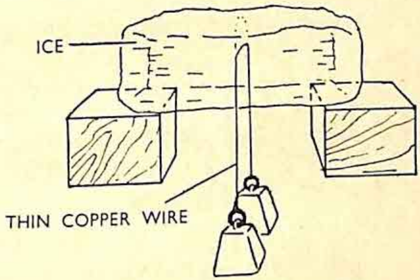


FIG. 36. Ice melting under pressure.

through the water that is formed. But as soon as the pressure has been removed, the water freezes again above the wire.

Although this lowering of the freezing-point is only slight, it has some important effects. A glacier 'flows' because the ice at the bottom of the glacier melts under the great pressure, and then freezes again when the pressure becomes less. In this way, also, glaciers can flow round a corner in a mountain valley and past rocks sticking up from the floor of the valley.

WHAT IS THE EFFECT OF PRESSURE ON THE BOILING-POINT OF WATER?

Increased pressure raises the boiling-point of water. When water boils, bubbles of steam are formed *inside* the liquid and rise to the surface. It is clear that such bubbles can only exist inside the liquid

if the pressure of the steam inside the bubbles is equal to the air pressure on the surface of the liquid. If the pressure on the surface were reduced, we should expect bubbles of steam to form more readily inside the liquid, and this is what happens in practice. Conversely, if the pressure on the surface of the liquid were *increased*, we should expect bubbles of steam to be formed *less*

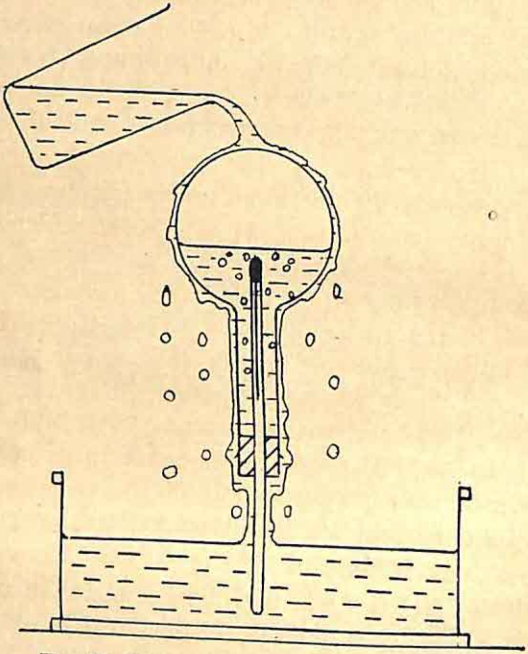


FIG. 37. Water boiling under reduced pressure.

readily, and this, too, is what we find by experiment. *An increase of pressure raises the boiling-point, and a decrease in pressure lowers the boiling-point.*

It is easy to show the effect of reduced pressure on the boiling-point of water. A round-bottomed flask is half filled with water and boiled for a few minutes until most of the air inside the flask has been driven out by steam. The flask is removed from the flame and

closed with a rubber cork carrying a thermometer. The closed flask is then inverted as shown in Fig. 37 and is cooled by pouring cold water over it. The inside temperature soon falls below 100° C., but when cold water is poured over the flask, the water inside begins to boil again because, as the steam condenses, the pressure inside the flask is reduced. The water continues to boil even when the flask becomes cool enough to be held on the palm of the hand.

As a result of this lowering of boiling-point by reduction of pressure, water boils at a lower temperature at the top of a mountain than at sea level. For example, at the South Col Camp on Mount Everest (26,000 ft.), water boiled at 73° C. Under such conditions, it is necessary to use *pressure cookers* (specially designed closed vessels fitted with safety-valves) in order to increase the pressure on the water until its boiling-point is high enough for cooking.

If the pressure on the surface of water is *increased*, its boiling-point is *raised*. In the boiler of a steam-engine, for example, the boiling-point under a pressure of 100 lb. wt. per square inch is 165° C., and at 125 lb. wt. per square inch it is 175° C. With modern steam-engines and steam-turbines, even higher pressures are used so as to get hotter steam possessing more energy. Some steam boilers produce a pressure of 1,400 lb. wt. per square inch (= 100 atmospheres) and the steam is at a temperature of over 500° C., i.e. the steam is 'red-hot'. In this way the *thermal efficiency* (see pp. 81–83) of the best steam engines has been increased by about 50 per cent. in recent years.

A SUMMARY OF THE EFFECT OF HEAT ON THE VOLUME OF WATER IN ITS THREE STATES

It is interesting to trace the effect of continued heating of water in its different states—ice, water, steam. If we start with a piece of ice at − 10° C. and heat it gradually, the first effect is that the ice will expand slightly like any other solid, until its temperature reaches 0° C. At this point the temperature will remain steady until all the ice has melted, forming about nine-tenths of its volume of

water. *When all the ice has melted*, the temperature will begin to rise again, and the water will *contract* slightly until the temperature reaches 4° C. After this the water will *expand* until the temperature reaches 100° C., when the temperature will remain steady until all the water has boiled away, forming 1,700 times its own volume of steam. On further heating, this steam, like any other gas, will expand in proportion to its Absolute temperature (Charles's Law) if the pressure remains constant.

MELTING-POINTS

The temperature at which a solid melts is called the *melting-point* of the substance and this, of course, is also the temperature at which the corresponding liquid solidifies. Nearly every pure *crystalline substance* has its own characteristic melting-point, at which the temperature remains steady until *change of state* is complete. Many substances can be recognized by their melting-points. *Non-crystalline substances* like glass, pitch, and glue, however, do not have definite melting-points, but they gradually become softer and softer as the temperature rises, and the same is true of mixtures of pure substances that have different melting-points. This fact is put to practical use in making 'soldered' joints. Pure lead melts between 327° C. and 328° C., but a mixture of lead and tin (solder) is liquid between 190° C. and 220° C. Hence two pieces of lead pipe can be 'soldered' together without melting the ends of the pipes and with plenty of time to shape the joint before the solder solidifies.

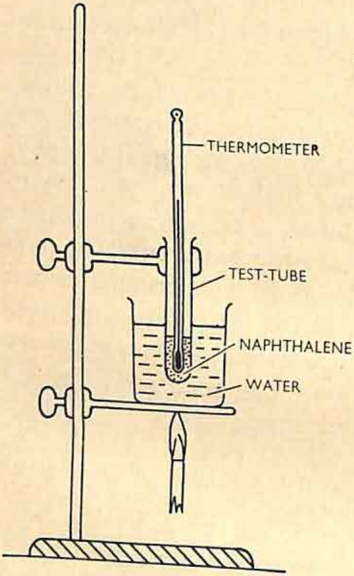


FIG. 38. Change of state.

The following experiment shows the temperature changes that take place when a solid melts:

Put about 5 gm. of powdered naphthalene in a 1-inch test-tube and place a thermometer so that its bulb is surrounded by the naphthalene. Clamp the test-tube in a beaker of water as shown in Fig. 38, put another thermometer in the water and heat over a Bunsen burner until the temperature of the *water* is between 65° C. and 70° C. Then turn down the flame and take the temperature of the *naphthalene* every half-minute until all the naphthalene has melted, recording your figures below (*a*). When all the naphthalene has melted, turn out your burner and let the water cool, again taking the temperature of the naphthalene every half-minute and recording your figures below (*b*).

TIME	0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6	6½	7	7½
TEMP. (*a*) . . .																
TEMP. (*b*) . . .																

Draw two graphs with *time* plotted horizontally and *temperature* plotted vertically as in Fig. 39.

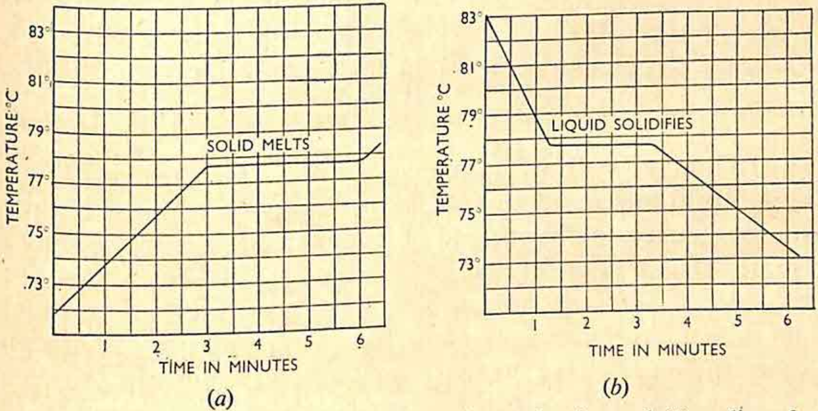


FIG. 39. Time-temperature graphs illustrating (*a*) heating and (*b*) cooling of naphthalene.

Notice that the temperature of the naphthalene remains steady during *change of state* from solid to liquid and from liquid to solid.

For practical purposes, melting-points are usually found by the following method.

HOW TO FIND THE MELTING-POINT OF A SOLID

(i) Draw out a piece of glass tubing so as to make a thin-walled capillary tube about 50 mm. long and 1 mm. in diameter. Seal up one end in the flame. Finely powder the given solid in a small mortar and fill the tube with the powdered substance to a depth of about 10 mm., tapping *gently* to shake it down the tube. Fasten the melting-point tube to a thermometer as shown in Fig. 40, using a small rubber band. Place the thermometer and melting-point tube in a 500 c.cm. beaker half filled with water, and heat over a wire gauze with a small flame, stirring all the time with a wire stirrer. When the solid melts, note the temperature.

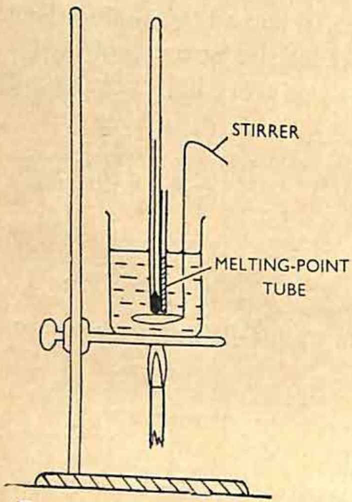


FIG. 40. Melting-point apparatus.

Melting-point of . . . .
= . . . . ° C.

(ii) To find the melting-point of some wax or fat, break off about 20 mm. from the closed end of the melting-point tube used in the last experiment and dip one end of it (to a depth of about 10 mm.) in some of the wax or fat that has been melted in a basin. Remove the tube and allow the wax to solidify. Then fasten the melting-point tube to the thermometer and find the melting-point as before. As fats and waxes have no sharp melting-point, this can be taken as the temperature at which the wax begins to rise in the tube.

Melting-point of. . . . . = ... ° C.

HOW TO FIND THE BOILING-POINT OF A LIQUID

Set up the apparatus shown in Fig. 41, and put about 20 c.cm. of the given liquid in the boiling-tube. Close the boiling-tube with a two-holed cork carrying a thermometer and a bent, *wide* glass tube.

If the liquid under test boils at a temperature of over 100° C., heat the boiling-tube over a small flame, using a wire gauze. If it boils below 100° C., clamp the boiling-tube with its lower end in a beaker of water. Heat the water in the beaker until the liquid in the inner tube boils, and then read the thermometer when the temperature becomes steady, being careful that the bulb of the thermometer is high enough to escape being splashed by the boiling liquid (see p. 7).

Boiling-point of................

= ....° C.

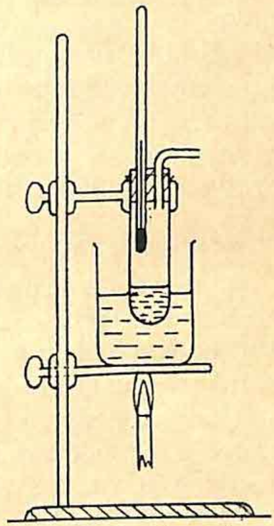


FIG. 41. Boiling-point apparatus.

EVAPORATION

A liquid can change into a gas or vapour without actually boiling. If, for example, water contained in a shallow dish is exposed to the air, it gradually changes into vapour, i.e. it *evaporates*. If the water is heated, this surface evaporation becomes more rapid, until, at the *boiling-point* of water, bubbles of vapour are formed *inside the liquid* and we say that the water *boils*. We have already studied the effect of changes of pressure on the boiling-point of water (see pp. 41–43).

If the dish of water is put into a closed space, e.g. under a closed bell-jar, the water will continue to evaporate for a time, but the process soon stops, because the space inside the bell-jar becomes *saturated with water-vapour*. If the temperature is raised, more water will evaporate; and if the temperature is lowered, part of the

water-vapour in the air will condense, leaving behind in the air of the bell-jar sufficient water-vapour to saturate it at the new temperature.

Evaporation can take place at any temperature, while *boiling* takes place at the boiling-point only.

MEASUREMENT OF HEAT AND HEAT-CAPACITY

We have seen that a *thermometer* measures *temperature* or '*hotness*'. A thermometer, however, will not measure the *amount of heat* contained in the hot material. If a thermometer is placed in a test-tube full of boiling water it will show the same *temperature* as when placed in a bucketful of boiling water, although there is clearly a big difference in the *quantity of heat* present in each case.

HOW TO MEASURE QUANTITY OF HEAT

When we are dealing with the *quantity of heat* in a hot body, it is clear that the *mass* of the hot material has to be considered as well as its temperature. The following experiment shows this:—

Take a metal can with its *sides* covered with a jacket of asbestos or cloth, and put into it 500 gm. (= 500 c.cm.) of tap-water. Clamp a thermometer in the middle of the can with its bulb about one inch above the bottom. Adjust your burner to give a *small* flame, *and do not make any further adjustments during your experiments, so that the burner will supply heat at the same rate throughout*. Put a flame-steadier round the flame and also use a wind-shield to keep off currents of air. Read the temperature of the cold water carefully and record it on p. 49. Then place the can of water over the flame, noting the time with a clock or watch marked in seconds. Record the rise in temperature at the end of each minute for three minutes. Notice that the rise in temperature per minute is practically constant, showing that the can of water is receiving heat at a steady rate. Repeat your experiment, first with 400 gm. (= 400 c.cm.) and then with 300 gm. (= 300 c.cm.) of cold water, recording the rise in temperature every minute as before.

TIME	500 gm.	RISE	400 gm.	RISE	300 gm.	RISE
Start . .	°C.		°C.		°C.	
1 min. .	°C.	°C.	°C.	°C.	°C.	°C.
2 min. .	°C.	°C.	°C.	°C.	°C.	°C.
3 min. .	°C.	°C.	°C.	°C.	°C.	°C.

500 gm. of water was heated from ......° C. to ......° C. = ...° in 3 minutes.

Therefore, average rise of temperature per minute = ...°.

400 gm. of water was heated from ......° C. to ......° C. = ...° in 3 minutes.

Therefore, average rise of temperature per minute = ...°.

300 gm. of water was heated from ......° C. to ......° C. = ...° in 3 minutes.

Therefore, average rise of temperature per minute = ...°.

MASS OF WATER	AV. RISE OF TEMP. PER MIN.	RISE OF TEMP. × MASS OF WATER
500 gm.	°C.	
400 gm.	°C.	
300 gm.	°C.	

If your experiment has been done carefully, all the products in the last column will be practically the same. But the amount of heat supplied by the burner per minute was also constant, so this suggests that *we can measure the quantity of heat supplied by the burner per minute by multiplying the rise in temperature by the mass of water heated*. This principle is the basis of our *units of heat*. We can now define these units, (*a*) the *calorie*,† which is a small unit for scientific purposes, and (*b*) the *British thermal unit*,† a larger unit for engineering use.

UNITS OF HEAT

The *scientific unit of heat* is called the *calorie*, and this is *the amount of heat required to raise the temperature of 1 gram of water through 1° C.* Thus, when 100 gm. of water is warmed through 10° C., e.g. from 30° to 40° C., we say that 1,000 calories of heat have entered the water. We shall sometimes use a larger unit, the *kilogram-calorie*, or *kilo-calorie*, which is equal to 1,000 calories.

The *engineering unit of heat* is called the *British thermal unit* (B.Th.U.) and this is *the amount of heat required to raise the temperature of 1 pound of water through 1° F.* (1 B.Th.U. = 252 calories.)

A still larger practical unit is the *therm*† (= 100,000 B.Th.U.). In England, for example, coal-gas is sold according to its heating power, and gas companies charge so much per therm of heat-energy.

CAPACITY FOR HEAT (THERMAL CAPACITY)

When we carry out experiments to measure the amount of heat required to raise the temperature of equal masses of different substances through one degree, it is found that different amounts of heat are required, because different substances have different capacities for heat. The following experiments illustrate this.

HOW TO COMPARE THE HEAT-CAPACITIES OF WATER AND OF IRON

Take three metal cans, and put ½ lb. (= 226 c.cm.) of cold water in each. In one can, hang a ½-lb. iron weight in the water, and heat this can over a Bunsen burner until the water boils. In the meantime, take the temperature of the cold water in the other two cans with a thermometer and record it below. When the water in the first can has been boiling for a few minutes, take out the hot iron and transfer it immediately to one of the cans containing cold water. Stir, and read off the highest temperature reached. Then pour the ½ lb. of boiling water into the other can of cold water. Stir, and read off the highest temperature reached.

Temperature of cold water = ...°. Temperature of hot iron

= ......°. Temperature of hot water = ...°. Temperature of mixture of $\frac{1}{2}$ lb. cold water + $\frac{1}{2}$ lb. hot iron = ...°. Temperature of mixture of $\frac{1}{2}$ lb. cold water + $\frac{1}{2}$ lb. hot water = ...°.

Hence, $\frac{1}{2}$ lb. of cold water at ......° is warmed through ......° by $\frac{1}{2}$ lb. of hot iron at ......°, while $\frac{1}{2}$ lb. of cold water at ......° is warmed through ......° by $\frac{1}{2}$ lb. of hot water at ......°. This result suggests that the *heat-capacity*† of water is about ...... times greater than the heat-capacity of iron. (Actually, the difference is even greater than this because the iron cooled to a much lower final temperature than did the boiling water after entering the cold water.)

HOW TO COMPARE THE HEAT-CAPACITIES OF WATER AND BRASS

Repeat your experiment using a $\frac{1}{2}$-lb. brass weight in place of the iron.

Temperature of cold water = ...°. Temperature of hot brass = ...°. Temperature of hot water = ...°. Temperature of mixture of $\frac{1}{2}$ lb. of cold water + $\frac{1}{2}$ lb. of hot brass = ...°. Temperature of mixture of $\frac{1}{2}$ lb. of cold water + $\frac{1}{2}$ lb. of hot water = ...°.

Hence, $\frac{1}{2}$ lb. of cold water at ......° is warmed through ......° by $\frac{1}{2}$ lb. of hot brass at ......°, while $\frac{1}{2}$ lb. of cold water at ......° is warmed through ......° by $\frac{1}{2}$ lb. of hot water at ......°. This result suggests that the heat-capacity of water is about ...... times greater than the heat-capacity of brass. (As explained above, the actual difference is even greater than this.)

Similar experiments on mixing equal masses of other hot substances with cold water show that equal masses of different substances, cooling through one degree, give out very different quantities of heat. This quantity of heat is called the *heat-capacity* or the *thermal capacity*† of the substance. *The thermal capacity of a body is the amount of heat required to raise its temperature through 1°*. (Notice that there is no mention of the mass or weight of the body.) Taking equal quantities, almost all other substances require less heat than water to raise their temperature the same

amount: hence we say that *water has a greater thermal capacity than other substances.*

SPECIFIC HEAT

When studying density, we found that it was usually more convenient to *compare* the density of a substance with that of water, the *relative density* or *specific gravity* being the density of the substance compared with the density of water, or,

$$\text{SPECIFIC GRAVITY} = \frac{\text{DENSITY OF SUBSTANCE}}{\text{DENSITY OF WATER}}$$

In the same way, when dealing with the heat-capacity of different substances, it is usually more convenient to compare their heat-capacity with that of an equal mass of water, measuring *specific heat*† instead of *thermal capacity*.

$$\text{SPECIFIC HEAT} = \frac{\text{THERMAL CAPACITY OF SUBSTANCE}}{\text{THERMAL CAPACITY OF SAME MASS OF WATER}}$$

Notice that specific heat is only a *ratio*, i.e. it is represented only by a *number*. Since the thermal capacity of one gram of water is *one calorie*, this number is the same as *the number of calories required to raise the temperature of one gram of the substance through 1° Centigrade*, or the number of calories given out when the temperature of one gram of the substance falls through 1° C.

Comparing this explanation of specific heat with the definition of the *calorie*, it will be seen that *the specific heat of water is 1.* In defining specific heat (as with specific gravity) water is taken as the standard substance, and *the specific heat of a substance is its capacity for heat as compared with that of water.*

When we say that the specific heat of aluminium is 0·2, we mean that the heat-capacity of water is five times greater than that of aluminium; e.g. the heat required to raise the temperature of 1 gm. of water through 1° C. would raise the temperature of 1 gm. of aluminium through 5° C.

Notice that the heat-capacity of water is about 30 times greater than that of mercury; that is to say, the heat required to raise the

temperature of 1 gm. of water through 1° C. would raise the temperature of 1 gm. of mercury through 30° C. Hence mercury is a very suitable liquid for use in thermometers because very little heat is taken from the hot substance when its temperature is being measured. On the other hand, water is the most suitable liquid to use in a 'hot-water bottle' because in cooling down by (say) 20° C. it gives out far more heat than would the same mass of any other liquid or solid. The high specific heat of water enables living organisms (all of which contain much water) to store heat and thus maintain a more uniform body-temperature.

APPROXIMATE SPECIFIC HEATS OF SOME COMMON SUBSTANCES

WATER	= 1·000	ALUMINIUM	= 0·2	GLASS	= 0·16
MERCURY	= 0·033	COPPER	= 0·09	SAND	= 0·19
TURPENTINE	= 0·46	IRON	= 0·12	GRANITE	= 0·20
BRASS	= 0·09	AIR	= 0·25	BRINE	= 0·71

TO FIND THE SPECIFIC HEAT OF SOLIDS—METHOD OF MIXTURES

Your experiments on pages 50–51 illustrate a method for finding the specific heat of a substance by the '*method of mixtures*'. *When hot and cold substances are mixed, no heat-energy is lost, but the quantity of heat given up by the hot substance is equal to the quantity of heat gained by the cold substance.* This statement is sometimes called the '*heat equation*',† on which is based the '*method of mixtures*' for measuring specific heat.

HOW TO FIND THE SPECIFIC HEAT OF A SOLID

(i) *Simple Method.* Put about 200 c.cm. of water in a beaker and heat it over a wire gauze until its temperature is between 60° and 65° C. While this water is being heated, weigh the given thick metal vessel [1] (to the nearest gram) and record its mass below. Fill this thick metal vessel with tap-water and allow it to stand with a thermometer in it until the hot water is nearly ready. Then read the temperature of the tap-water (which will be the same as that of the metal) to the nearest 0·1° C. When the hot water is between 60°

[1] About 3¾ in. high, 2 in. inside diameter, and ¼ in. thick.

and 65° C., turn out the burner, stir the water, and read its temperature *accurately*. Then *quickly* pour out all the cold water from the thick vessel and nearly fill it with hot water from the beaker. There is a sudden fall in temperature as the hot water loses heat to the cold metal, but the temperature soon becomes almost steady. Stir *gently* and read off the final temperature accurately *as soon as it becomes steady*. Weigh the thick metal vessel with the water in it. (N.B.—In finding specific heats, it is most important to read the *temperature* as accurately as possible, because the error in reading the thermometer is large compared with the error in weighing.)

Mass of thick metal vessel . . .	= . . . . gm.
Mass of thick metal vessel and water .	= . . . . gm.
Therefore, mass of water . . .	= . . . . gm.
Original temperature of cold metal . .	= . . . . ° C.
Original temperature of hot water . .	= . . . . ° C.
Final temperature of metal and water .	= . . . . ° C.
Therefore, rise in temperature of metal .	= . . . . ° C.
And, fall in temperature of water . .	= . . . . ° C.

But, ... gm. of water, in cooling through . . . . ° C., gave out . . . . × . . . . = ... calories, and this quantity of heat raised the temperature of . . . . gm. of the metal through . . . . ° C. Therefore, the amount of heat required to raise the temperature of 1 gm. of the metal through 1° C.

$$= \frac{\qquad \text{cal.}}{\qquad \times \qquad}$$

$= \ldots\ldots\ldots$cal.

Therefore, specific heat of . . . . = ...

(ii) *More Accurate Method*. The last experiment is very simple, but it can only be used if suitable thick metal vessels are available. If the solid is in lumps, another method is used. Weigh the given piece of metal (to the nearest 0·1 gm.), and, after attaching a piece of thread by which to lift it, place it in a vessel containing water boiling over a burner. Weigh a thin-walled metal *calorimeter*† (a vessel in which heat-measurements are made), put into it sufficient

cold water to cover the piece of metal completely, and weigh again. Then take the temperature of the cold water *accurately* with a thermometer. When the metal has been in the boiling water for five minutes, lift it out and, giving it a quick shake so as to get rid of as much water as possible, transfer the hot metal *quickly* to the calorimeter (which has been placed inside a thick cloth jacket to reduce loss of heat). The hot metal will give up heat to the cold water, and the temperature of the water will rise. Stir gently, and note the highest temperature reached, reading the thermometer as accurately as possible. Record your figures below.

Mass of metal (....................) .	=	gm.
Mass of empty calorimeter . . .	=	gm.
Mass of calorimeter + water . . .	=	gm.
Therefore, mass of water . . .	=	gm.
Original temperature of water. . .	=	° C.
Original temperature of metal. . .	=	° C.
Final temperature of water and metal .	=	° C.
Therefore, rise in temperature of water .	=	° C.
And, fall in temperature of metal . .	=	° C.

But, by the '*heat equation*', heat lost by hot metal = heat gained by cold water, i.e. mass of metal × fall in temperature × specific heat = mass of water × rise of temperature × specific heat.

Therefore, ...(gm.) × ....(° C.) × specific heat = ... (gm.) × .... (° C.) × 1.

Therefore, specific heat of metal (.........) $= \dfrac{\quad \times \quad \times \quad}{\times}$

= ....

WATER EQUIVALENT OF CALORIMETER

In your last experiment, you assumed that all the heat given out by the metal in cooling was given up to the cold water. This is not true, because some heat was used in warming up the containing vessel. In your experiment, if you used a copper calorimeter, ... gm. of copper were heated through ....° C.

But the specific heat of copper is 0·1, i.e. copper has about one-tenth the thermal capacity of water. Hence the *thermal capacity* of your calorimeter is .... × 0·1 = ... calories, and the heat gained by the calorimeter in your experiment = ... × .... = ... calories. This is a fair amount of heat, and if you want to find the specific heat of the metal more accurately, this quantity of heat should be added to the right-hand side of your equation. (Notice that Experiment (i) on pp. 53–54 avoids this complication.)

If your calorimeter has a thermal capacity of .... calories, it has the same thermal capacity as .... gm. of water, hence it is convenient to call this mass of water *the water equivalent of the calorimeter*. Re-calculate the result of your last experiment, *adding the water equivalent of the calorimeter to the mass of the cold water*. More accurate specific heat of .... = ...

HOW TO FIND THE SPECIFIC HEAT OF A LIQUID

Having found the specific heat of .... in your last experiment, use your result to find the specific heat of a liquid, e.g. methylated spirit.

Heat your weighed piece of metal in boiling water as before. While the metal is being heated, put into the weighed calorimeter sufficient methylated spirit to cover the piece of metal completely, and weigh again. Put the cloth jacket on the can and then take the temperature of the spirit *accurately*. When the metal has been in the boiling water for five minutes, lift it out, shaking so as to remove as much water as possible, and transfer it *quickly* to the calorimeter. Stir, and note the highest temperature reached. Record your figures below.

Mass of metal (................) . .	=	gm.
Specific heat of	=	
Mass of empty calorimeter . . .	=	gm.
Mass of calorimeter and methylated spirit	=	gm.
Therefore, mass of methylated spirit .	=	gm.
Original temperature of methylated spirit .	=	°C.

Original temperature of metal . . . $= \dots\dots\dots$ °C.
Final temperature of methylated spirit and metal . . . . . . $= \dots\dots\dots$ °C.
Therefore, rise in temperature of methylated spirit . . . . . $= \dots\dots\dots$ °C.
And, fall in temperature of metal . . . $= \dots\dots\dots$ °C.

But, by the '*heat equation*', heat gained by liquid = heat lost by metal, i.e. mass of liquid × rise in temperature × specific heat = mass of metal × fall in temperature × specific heat of metal.

Therefore, ...(gm.) × ....(° C.) × specific heat = ... (gm.) × .... (° C.) × ....

$$\text{Therefore, specific heat of methylated spirit} = \frac{\quad\times\quad\times\quad}{\quad\times\quad}$$

$$= \dots\dots\dots\dots\dots$$

(Re-calculate your result, allowing for the heat gained by the cold calorimeter.

Thermal capacity of copper calorimeter = ... × 0·1 = ... cal.

Therefore, water equivalent of calorimeter = ... grams of water.)

More accurate specific heat of methylated spirit = ...

CHANGE OF STATE AND LATENT HEAT

In our earlier work we have learnt that matter can exist in three different *physical states:* as a *solid*, as a *liquid*, or as a *gas*; and that, by suitable heating or cooling, it is possible to change most substances into any other of these three states. The changes from solid to liquid and back again from liquid to solid, or from liquid to gas and back again from gas to liquid, are accompanied by important heat effects.

For example, when a vessel of crushed ice is placed in a warm room, the temperature of the melting ice remains constant at 0° C. as long as any ice remains unmelted. (We make use of this

fact in marking the lower fixed point on a thermometer.) Although the temperature of the ice has not risen, heat from the warm air has been passing into the ice all the time that it has been melting. As soon as all the ice has melted, the temperature of the water begins to rise and continues to rise until it reaches the same temperature as the room. We have seen that the same thing happens when naphthalene melts (see page 45).

Similarly, when a vessel of water is heated over a burner, the temperature of the water rises until it boils at 100° C. But all the water is not changed into steam immediately; and, although the water continues to receive heat from the burner, the temperature remains steady at 100° C. until all the water has boiled away. (We make use of this fact in marking the higher fixed point on a thermometer.)

Thus, when ice melts and when water boils, heat is being supplied to the substance *without producing any rise of temperature*. This heat is called *latent heat*† because it seems to be hidden (or latent)* in the ice or water. Actually, its energy has been used in changing the condition of the molecules. When ice melts, heat is used in producing a less orderly arrangement, overcoming the molecular attractions in the rigid geometry of the ice. When water boils, heat is used in overcoming the attraction between the molecules of the liquid, i.e. in forcing them further apart.

The latent heat of fusion of a substance is the number of calories required to change one gram of it from the solid state to the liquid state without change of temperature.

The latent heat of vaporization of a substance is the number of calories required to change one gram of it from the liquid state to the gaseous state without change of temperature.

THE LATENT HEAT OF FUSION OF WATER (OR THE LATENT HEAT OF MELTING OF ICE)

The latent heat of fusion of water (*or the latent heat of melting of ice*) *is the number of calories required to change one gram of ice at 0° C. into one gram of water at 0° C.*

If some crushed ice is heated over a small, steady flame, it is found that it takes about 80 times as long to melt the ice as it does to raise the temperature of the resulting water through 1° C.

Hence we conclude that it requires about 80 calories of heat to melt 1 gram of ice. We can measure this quantity more accurately by the method of mixtures, i.e. by mixing a known mass of melting ice with a known mass of warm water and measuring the fall in temperature of the water.

HOW TO FIND THE LATENT HEAT OF WATER

Weigh a copper calorimeter. Half fill it with warm water at about 40° C. and weigh again. Break up some ice into small pieces and wrap it up in a duster.* Put the cloth jacket round the calorimeter can and take the temperature of the warm water *accurately*. Then add pieces of ice (first removing as much water as possible with the duster), stirring *gently* with a thermometer until the temperature falls to about 25° C. and all the ice that has been added is just melted. Note the lowest temperature reached, and then weigh the calorimeter and its contents.

Mass of empty calorimeter . . .	= . . . . gm.
Mass of calorimeter + warm water . .	= . . . . gm.
Therefore, mass of warm water . .	= . . . . gm.
Specific heat of copper	= 0·1 cal per gm.
Mass of calorimeter + warm water + ice water	= . . . . gm.
Therefore, mass of ice added . . .	= . . . . gm.
Original temperature of warm water .	= . . . . ° C.
Original temperature of ice . . .	= . . . . ° C.
Final temperature of mixture . . .	= . . . . ° C.
Therefore, rise of temperature of melted ice	= . . . . ° C.
Fall in temperature of warm water and calorimeter	= . . . . ° C.

Notice that the heat gained by the melting ice will have to be

considered in two parts, (i) *the heat required to melt the ice*, and (ii) *the heat required to raise the temperature of the ice-water from 0° C. to the final temperature of the mixture.*

By the '*heat equation*', heat gained by ice = heat lost by warm water and by warm calorimeter.

Therefore, (latent heat of ice × mass of ice) + (mass of ice-water × rise in temperature × specific heat of water) = (mass of warm water × fall in temperature × specific heat of water) + (mass of copper × fall in temperature × specific heat of copper).

Therefore, (latent heat × .... (gm.)) + (.........(gm.) × .... (° C.) × 1) = (......... (gm.) × .... (° C.) × 1) + (......... (gm.) × .... (°C.) × 0·1).

Therefore, latent heat of water = ... calories per gram.

According to the most careful measurements, the *latent heat of fusion of water* (or the *latent heat of melting of ice*) *is 80 calories per gram*, i.e. it requires as much heat to melt one gram of ice as to raise the temperature of one gram of water from 0° C. to 80° C. Conversely, since it takes 80 calories of heat to melt one gram of ice, this amount of heat must be given out again when one gram of liquid water freezes.

Different substances have different latent heats of melting, but most other solids have a smaller latent heat of melting than ice.

THE LATENT HEAT OF STEAM (OR THE LATENT HEAT OF VAPORIZATION OF WATER)

The latent heat of steam (or the latent heat of vaporization of water) is the number of calories required to convert 1 gram of boiling water at 100° C. into 1 gram of steam at the same temperature.

HOW TO FIND THE LATENT HEAT OF STEAM

(i) *Simple Method.* The easiest way of measuring the latent heat of steam approximately is to pass a known mass of steam into a cold metal vessel whose thermal capacity is known, and then

measure the rise in temperature produced. Quarter fill a flask or steam-can with water and put it over a burner to boil. While this water is being heated, weigh (to the nearest gram) the thick metal vessel used to find the specific heat of . . . . (see pp. 53–54). Surround this vessel with a cloth jacket, fill it with cold tap-water, and allow it to stand with a thermometer in it until the water in the steam-can is boiling. Then read the temperature of the cold water (which will be the same as that of the metal vessel) to the nearest 0·1° C. Empty out this cold water, shaking out the last few drops; close it with a large rubber stopper carrying two glass tubes, and then invert it over the steam-can as shown in Fig. 42. Steam at 100° C. passes into the cold metal vessel and condenses, giving up its *latent heat* to the cold metal and raising its temperature. When the temperature of the thick metal vessel reaches 100° C., no more steam will condense, but steam will begin to escape freely from the right-angled outlet tube. When this happens, remove the thick metal vessel from the steam-can, take it out of its jacket and let it cool. Then carefully remove the stopper and measure the volume of the condensed steam by pouring it into a burette.

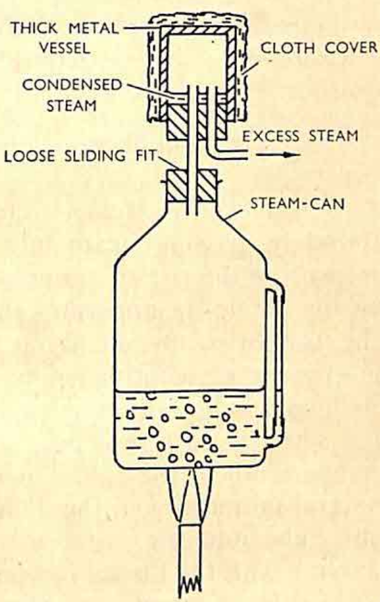


FIG. 42. Finding the latent heat of steam by a simple method.

Mass of thick . . . . vessel	=	gm.
Specific heat of	=	
Volume of condensed steam	=	c.cm.
Therefore, mass of condensed steam	=	gm.
Original temperature of metal vessel	=	° C.

Final temperature of metal vessel . . = ... °C.
Therefore, rise in temperature of metal vessel . . . . = ... °C.

By the '*heat equation*', heat lost by steam = heat gained by vessel.

Therefore, mass of steam × latent heat = mass of metal × rise in temperature × specific heat.

Therefore, ...(gm.) × latent heat of steam = ... (gm.) × .... (°C.) × ....

Therefore, latent heat of steam = $\frac{\quad \times \quad \times \quad}{\quad}$ = ... cal. per gm.

(ii) *Alternative Method.* The latent heat of steam can also be found by passing steam into a known mass of cold water and measuring the rise of temperature produced by a known mass of steam. Set up the apparatus shown in Fig. 43 and boil the water in the flask or steam-can. While this water is being heated, weigh an empty copper calorimeter, to the nearest 0·1 gm. Then half fill it with cold water, and weigh again. Put a cloth jacket round the can (or stand it on three corks inside a larger vessel), and take the temperature of the cold water. Allow steam to escape freely for several minutes from the delivery-tube [1] and then dip the end of this tube into the water in the calorimeter. Pass in dry steam, stirring with the thermometer until the temperature rises to about 45° C. Then remove the steam-tube *quickly* and go on stirring until the temperature begins to fall again. Note the highest temperature reached, and then weigh the calorimeter again.

Mass of empty calorimeter . . . = ... gm.
Mass of calorimeter + cold water . . = ... gm.
Therefore, mass of cold water . . . = ... gm.
Mass of calorimeter + mixture . . = ... gm.
Therefore, mass of steam added . . = ... gm.

[1] The steam-tube should be wrapped with thick string (preferably asbestos-string) to prevent the steam from condensing before it reaches the calorimeter, for we want to mix *dry steam* (and not hot water) with the cold water in the calorimeter.

Temperature of cold water and calorimeter = ... °C
Temperature of steam . . . . = ... °C.
Temperature of mixture . . . . = ... °C.
Therefore, rise in temperature of cold water and calorimeter. . . . . . = ... °C.
And, fall in temperature of condensed steam = ... °C.
Thermal capacity of copper calorimeter = ... ×0·1 = ... cal.

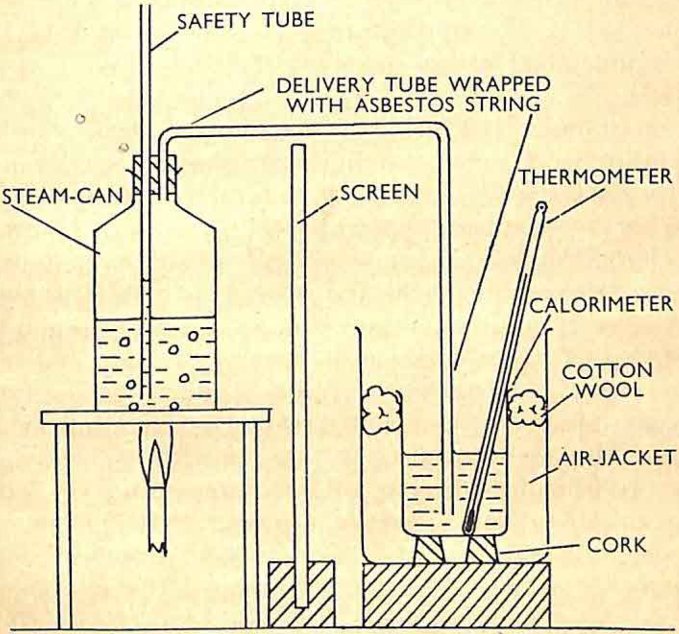


FIG. 43. Finding the latent heat of steam more accurately.

Therefore, water equivalent of copper calorimeter = ... gm. of water.

By the '*heat equation*', heat lost by steam = heat gained by cold water and calorimeter.

But the heat lost by the steam must be considered in two parts:

(i) *the latent heat given out by the steam at 100° C. in condensing into water at 100° C.*, and (ii) *the heat given out by the condensed water in cooling down from 100° C. to the final temperature of the mixture* (.......... °C.).

Therefore, heat lost by steam in changing to water at 100° C. + heat lost by condensed steam in cooling to final temperature of mixture = heat gained by cold water and calorimeter.

Therefore, (latent heat of steam × mass of steam) + (mass of steam × fall in temperature × 1) = (mass of cold water + water equivalent) × rise in temperature × 1.

Therefore, (latent heat of steam × ...... (gm.)) + (...... (gm.) × .... (°C.)) = (........ + ... (gm.)) × .... (°C.)

Therefore, latent heat of steam = ... cal. per gm.

According to the most careful experiments, *the latent heat of steam* (or *the latent heat of vaporization of water*) *is 536 calories per gram*, i.e. *to convert 1 gram of boiling water at 100° C. into 1 gram of steam at the same temperature requires 536 calories of heat*; or, it requires 536 times as much heat to change 1 gram of water at 100° C. into steam at 100° C. as it does to heat 1 gram of water from 99° to 100° C.

When steam condenses to water, it gives out just as much heat as was required to vaporize it, so that when 1 gm. of steam at 100° C. condenses to water at 100° C. it gives out 536 calories of heat. One practical result of this is that 1 gm of steam at 100° C. contains more energy than 1 gm. of boiling water at 100° C. Hence a burn from steam is more severe than a burn from boiling water, although both may be at the same temperature.

EVERYDAY APPLICATIONS AND EFFECTS OF LATENT HEAT

(*a*) *The cooling effect of melting*

In an ice-box, for every gram of ice melted, 80 calories of heat are taken from the air and food inside the ice-box. Hence, if heat does not enter from outside, a little ice will have a big cooling effect. Once the ice has melted, the water, which is still at a low

temperature, continues to take heat from the surroundings, but the cooling effect is now very slight because latent heat is no longer involved. Ice-boxes are *heat-insulated*, i.e. they are made with double walls, the space between these being packed loosely with a porous material (see p. 33). The air between the double walls is a poor conductor of heat, hence little heat enters the ice-box from outside. If we can make ice melt more quickly, e.g. by adding salt, latent heat will be taken from the surroundings more quickly, and we have a *freezing mixture* (see p. 40).

(*b*) *The cooling effect of evaporation*

When a liquid evaporates, it absorbs heat (latent heat) either from itself or from its surroundings, which are therefore cooled. Examples of this cooling effect are:

(i) Petrol, when spilt on the hand, feels cold.

(ii) Damp clothes feel cold, especially when the air is dry and when there is a breeze. If one sits about in damp clothes, the rapid cooling effect on the body, though not itself dangerous, is likely to lower one's resistance to disease, e.g. to the common 'cold'.

(iii) Water can be kept cool in canvas bags exposed to the wind, or in porous earthenware vessels. The latent heat required for evaporating the thin film of water on the outside of the porous material is taken from the water inside, hence its temperature is lowered. (We shall see that the wet-bulb thermometer is cooled in the same way—see pp. 67–68). This cooling effect is only obtained if the air surrounding the damp cloth or earthenware is sufficiently dry to allow evaporation.

(iv) Our bodies lose heat by evaporation of sweat, which is mainly water, from the skin. When we consider that in a tropical climate a healthy man may lose several litres of water per day by sweating, and that each litre of water requires over half-a-million calories for its evaporation, it is clear that very large amounts of heat are removed from the body by evaporation of sweat. Notice, however, that sweating has no cooling effect *unless the sweat evaporates*.

WATER VAPOUR IN THE ATMOSPHERE

Owing to constant evaporation from seas, lakes, and rivers, and because of the *transpiration* of plants, the air always contains water vapour, varying in amount from place to place, from day to day, and even from hour to hour. The presence of this water vapour is shown by the drops of water that form on the outside of a vessel containing ice-water. The measurement of the amount of water vapour in the air is called *hygrometry*,† and the instruments by which it is measured are called *hygrometers*.†

Usually, the air is not completely saturated with water vapour, but if it is cooled sufficiently it will become saturated, and any excess of water vapour will condense as *dew*, *cloud*, *rain*, or *mist*, according to the conditions under which cooling takes place.

MEASUREMENT OF THE DAMPNESS OF THE AIR

There are various ways of measuring and expressing the dampness of the air; we shall deal with them briefly in turn and then discuss their practical value in everyday life.

(i) *The actual vapour pressure*. If some water is put into a corked bottle containing dry air, the water begins to evaporate and its vapour sets up a '*vapour pressure*'† that can be measured, e.g. in a barometer tube. If there is an excess of water, evaporation continues until the air is *saturated*; it can then hold no more water vapour and the vapour pressure reaches its maximum figure for that particular temperature. For example, at 10° C. the saturated vapour pressure of water is 9·2 mm. of mercury; at 20° C. it is 17·5 mm.; at 30° C. it is 31·8 mm.; at 40° C. it is 55·3 mm. of mercury. Normally, air is unsaturated and the water vapour is not exerting its maximum vapour pressure. We can therefore express *humidity* (the degree of dampness of the air) as *either* the vapour pressure itself, *or* as the *saturation deficit**† (which means the difference between the actual vapour pressure of the atmosphere and the vapour pressure of a saturated atmosphere at the same temperature). For example, suppose that at a temperature of 30° C. (= 86° F.) the *actual* vapour pressure were 19·1 mm., then

the *saturation deficit* would be $(31{\cdot}8 - 19{\cdot}1) = 12{\cdot}7$ mm. of mercury. A knowledge of *saturation deficits* is useful because evaporation from wet surfaces is often proportional to it.

(ii) *The dew point*. Air that is not already saturated with water vapour will become saturated if the temperature is sufficiently lowered, and the *dew point*† *is the temperature to which the air must be cooled before it begins to deposit water on a surface*. In other words, it is the temperature at which the water vapour actually present in the air would completely saturate it.

The simplest method of finding the dew point is to cool a polished metal vessel very slowly until dew first appears on its surface. Take a polished aluminium cup, and half fill it with water at room temperature. Drop into it small pieces of ice, one at a time, stirring *gently* with a thermometer, and allowing each piece of ice to melt before adding another. Be careful not to breathe on the vessel: place a sheet of glass in front of it. Watch the polished metal surface very carefully, occasionally stroking it with a bit of cotton-wool to show up the dew, and read the thermometer as soon as dew appears. This temperature is the *dew point* = ... ° F. Note also the *air temperature* = ...° F.

The dew point gives a useful indication* of the amount of water vapour present (i.e. its vapour pressure), but unfortunately neither dew point nor vapour pressure are easy to measure accurately by direct methods. We can, however, obtain figures for dew points and vapour pressures from prepared tables [1] if we read the temperatures of the *wet-bulb and dry-bulb thermometers*.

(iii) *Wet-bulb and dry-bulb thermometers*. This is the simplest instrument for measuring humidity. It depends on the principle of cooling by evaporation. To show how the instrument works, take two similar Fahrenheit thermometers and hang them up side by side *in a current of air*. Wrap a piece of cotton cloth round the bulb of one thermometer and allow the free end to dip into water so as to keep the bulb wet, as shown in Fig. 44. If the surrounding air is

[1] e.g. *The Meteorological Observers' Handbook* or *The Air Ministry Hygrometric Tables*.

not saturated, water will evaporate from around the wet-bulb and the necessary *latent heat* will be taken from the mercury in the thermometer bulb. In this way, if the air is not saturated with water vapour, the wet-bulb thermometer will show a lower temperature than the dry-bulb thermometer. If the air is already saturated with water then there can be no evaporation from the wet-bulb and there will be no fall in temperature, so that both

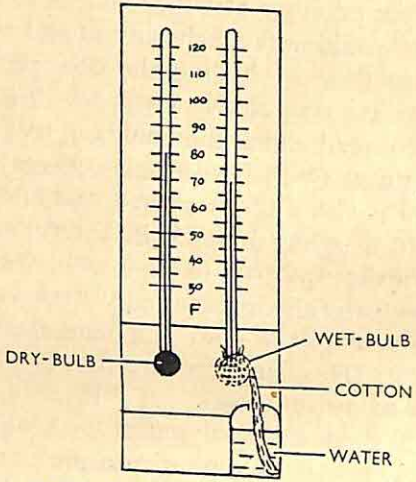


FIG. 44. Wet-bulb and dry-bulb thermometers.

thermometers will show the same reading. If the air is very dry, then there will be rapid evaporation from around the wet-bulb and the readings of the wet-bulb thermometer will be much lower than those of the dry-bulb thermometer. Set up wet-bulb and dry-bulb thermometers in your class-room and take daily readings throughout the school year.

(iv) *Relative humidity.* The commonest way of expressing humidity is by stating the *relative humidity*, i.e. the degree of saturation (expressed as a percentage) at any given temperature.

$$\text{RELATIVE HUMIDITY} = \frac{\text{QUANTITY OF WATER ACTUALLY PRESENT}}{\text{QUANTITY REQUIRED TO SATURATE THE AIR AT THE SAME TEMPERATURE}}$$

In practice, this way of expressing humidity is probably the least valuable of all, although it is still in everyday use. We have already learnt that evaporation is often proportional to *saturation deficit*. Now while it is true that, for any given temperature, saturation deficit can be calculated from relative humidity (see p. 66), nevertheless a relative humidity of (say) 50 per cent. may refer to different vapour pressures and saturation deficits. Thus, for a relative humidity of 50 per cent. at 20° C. (= 68° F.), the saturation deficit is 8·77, while at 35° C. (= 95° F.) it is 21·09. This means that, other things being equal, water will evaporate much faster at 95° F. with a relative humidity of 50 per cent. than at 68° F. and *with the same relative humidity of* 50 *per cent*.

You can find the relative humidity, if you have read the wet-bulb and dry-bulb thermometers, by looking up tables in *The Meteorological Observers' Handbook*, which lists relative humidity and vapour pressure for any pair of dry-bulb and wet-bulb readings. A simple direct comparison of relative humidities is also given by timing the rate of change in the colour of cobalt chloride paper.

THE VALUE OF HUMIDITY MEASUREMENTS

A knowledge of the humidity of the atmosphere is important to meteorologists;* to botanists and agriculturists in connection with transpiration; to foresters in connection with forest fires; to physiologists* and those that decide the conditions under which men may work in factories and mines.

A knowledge of the relative humidity is not of much value in such work, however, even if the temperature is known, because it tells us, for example, little about *bodily comfort*. But we can at least see the effects of relative humidity, e.g. (i) when the relative humidity is high, table-salt gets sticky and clothes become damp to the touch and may go mouldy if temperatures are high enough; (ii) when the relative humidity is low, grass and trees burn readily. Pieces of wood, dead leaves, etc., actually weigh less when the relative humidity is low, hence foresters sometimes estimate 'fire

risk' by weighing a standard piece of soft wood that has been kept out of doors.

Physiologists, concerned with transpiration in plants and with the cooling effect of evaporation of sweat (e.g. in studies of air-conditioned rooms and trains) no longer use relative humidity as a useful indicator; they use either the *vapour pressure* or the *saturation deficit* figures, together with the temperature, or they rely directly upon their knowledge of the difference between dry-bulb and wet-bulb readings.

DISCOMFORT DUE TO HEAT

An air temperature of 95° F., or higher, is uncomfortable to most people, and one above 105° F. is very uncomfortable. But healthy human beings can stand air temperatures higher than their body-temperature because the body *cools itself* by turning water into water vapour, which is lost in the breath and by evaporation from sweat-pores. If the air already contains much water vapour (at a vapour pressure of more than half an inch) this cooling effect is insufficient. Hence, when the relative humidity is high, a temperature of 80°–85° F. may be very uncomfortable. Such a condition is common in the wet tropics, where the vapour pressure may reach 25 mm. of mercury. The relation between wet-bulb temperature and humidity is complicated, but a wet-bulb temperature of 70° F. is always uncomfortable. In the wet tropics, the wet-bulb temperature may exceed 70° F. for months on end.

HOW DEW IS FORMED IN NATURE

The surface soil continually gives out heat to the atmosphere. During the night the surface becomes cooler than the air above, and the soil just below the surface has a store of heat that slowly passes upwards, but this process is too slow to balance heat-loss by radiation from the soil surface. If the top-soil is loose (e.g. after digging or ploughing) the surface cools more rapidly, because conduction from below is very slow. The minimum temperature of the soil surface is often 6–8° F. below the minimum

air temperature measured at a height of three feet above the ground.

In this way, the temperature of the soil, and of the air in direct contact with it, may fall below the dew point, and dew is deposited on grass or soil, or on any radiating object. Thus dew 'falls'. (It can also 'rise'—that is, water vapour can rise from the warm subsoil and condense at the surface—but this is not so important.) If a wind is blowing, the cool air near the ground is mixed with the warmer air a few feet above the surface, and dew is less likely to form.

MIST AND FOG; CLOUDS AND RAIN

If the air temperature falls below the dew point, tiny droplets of water condense on floating dust particles, forming a *mist*, not only near the ground, but also extending upwards for a few hundred feet. A very dense mist is called a *fog*. Mist and fog sometimes form near the sea-coast when warm, damp winds blow inland over *cold* ground. Mist and fog may also form over low-lying country, over ponds, swamps, rivers, and lakes, where the humidity is high and where radiation at night cools the air sufficiently to bring it below the dew point. Such mist and fog is characteristic of calm weather, and a misty morning is usually followed by a fine day. Fogs are usually worst over cities, where the air contains more dust particles.

Clouds are formed in the same way as mist or fog, by the cooling of damp air. This cooling may be brought about in several ways, the commonest of which is *expansion*. When air is heated, it expands in volume. If, on the other hand, air is made to expand without adding heat to it, then it becomes cooler; the heat required for its expansion being *taken from the gas itself*. Now, when air near the Earth's surface is warmed, its density becomes less and the warm air rises. As it does so its pressure decreases (see Book Two, Chap. IV) and the air therefore *expands*. In doing so it *cools itself* and, if the humidity is high, a *cloud* forms.

The cooling effect of expansion and the formation of clouds can be demonstrated by the following experiments: A bell-jar or bottle,

with a thermometer in it, is connected to an air-pump and most of the air inside is pumped out. After waiting until the temperature is the same inside and outside, we open the tap or screw-clip and admit air into the vessel. The air expands suddenly as it enters the partial* vacuum. The temperature inside the vessel falls slightly, showing that the air has cooled itself by expansion (see Fig. 45). If the experiment is done when the air is nearly saturated with water vapour, a cloud is formed inside the vessel as the air rushes in. (If the air that is admitted is dusty or smoky, cloud-formation is more striking—see p. 71.)

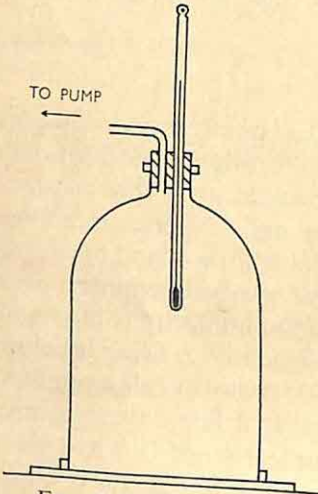


FIG. 45. Cooling effect of expansion.

Clouds of different kinds form at various heights up to six miles. Clouds are often formed on the windward side of mountains because when warm, wet winds meet the mountain range, they are deflected* upwards, and the rising air expands and cools itself to below the dew point. Air is also cooled by loss of heat to cold land or sea. When a warm, wet wind meets a cooler one, vapour condenses in droplets until they become big enough to fall as *rain*. If the temperature at which the water vapour condenses is below 0° C., then the condensing water vapour forms *snow*. When violent air-currents, which often accompany thunder-storms, carry raindrops and snow up and down through layers of damp air cooled below 0° C., *hail-stones* are formed. If large hail-stones are cut across, they show concentric* layers of ice and snow. 'And every layer means a tumultuous* journey of thousands of feet upward, thousands of feet back, and thousands of feet up again. Hailstones are the most dramatic* of water's forms.'[1]

[1] *Weather*—G. Pickwell.

THE RELATION BETWEEN HEAT AND WORK

We already know that heat is a form of energy. By this we mean that heat is capable of *doing work*; that heat may be transformed into mechanical energy; and that mechanical energy may be transformed into heat.

There are many everyday examples of the change of mechanical *work* into *heat*. A bicycle-pump becomes hot when the tyre is pumped up. Tools for boring holes in wood or metal become very hot in use. Saws become hot while sawing; pieces of metal become hot when hammered; the brakes of bicycles and motor-cars become hot when used; a bullet* fired from a rifle* becomes hot when it is stopped by a metal plate (a lead bullet becomes so hot that it melts). In all these examples, work has been transformed into heat.

THE MECHANICAL EQUIVALENT OF HEAT—JOULE'S EQUIVALENT

In 1840, *Joule* began his famous experiments to find the exact relation between heat and work, or what is called *the mechanical equivalent of heat*, i.e. the mechanical energy that disappears in producing a known quantity of heat-energy.

Joule's method was to convert mechanical work into heat by using the work to stir water in a calorimeter, thus raising its temperature. The work was supplied by letting known masses fall through a measured distance so that the amount of mechanical work done could be calculated. (The practical *unit of work* is a *foot-pound*,† the amount of work done when a mass of *one pound* is raised through a vertical height of *one foot*.) The weights were attached to strings wrapped round the axle of the stirring apparatus so that when the weights fell they turned the stirrer in the calorimeter, thus raising the temperature of the water (see Fig. 46). The amount of heat produced was measured by multiplying the mass of the water by the rise in temperature. As the rise in temperature was very small, very great accuracy was required in Joule's

experiments, which are still regarded as models of how scientific work should be carried out.

As the result of a large number of careful experiments, Joule found that *777 foot-pounds of mechanical work will raise the temperature of one pound of water through 1° F.* That is, *one British thermal unit of heat = 777 foot-pounds of mechanical work*. This is called *Joule's equivalent*, or *the mechanical equivalent of heat*.

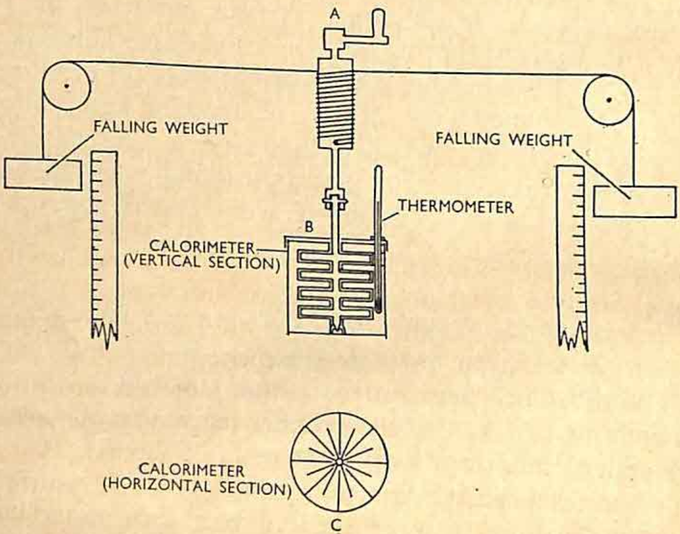


FIG. 46. Joule's experiment (diagrammatic).

Conversely, if 1 B.Th.U. could be completely converted into mechanical work, it would lift a mass of 777 lb. through a vertical height of 1 ft. We shall learn more about mechanical work in later lessons.

When we come to study *machines* (devices for performing work) in Book Four, we shall find that some of the work done on the machine is wasted in overcoming *friction*. This wasted work, however, is not destroyed, it appears as *heat*. *When energy is supplied to a machine, an exactly equivalent amount of energy is produced, either*

as useful work or as heat, and, conversely, *when heat disappears, an exactly equivalent amount of work is always obtained*. This is an example of the *law of the conservation* of energy*, i.e. '*Energy can be neither created* nor destroyed*'.

Joule's experiment was concerned with the conversion of mechanical energy into heat-energy. *Heat-engines* are concerned with the converse operation, *the conversion of heat-energy into mechanical energy*. These heat-engines are very important in every-day life since they supply the enormous amounts of mechanical energy used by civilized man.

The term *heat-engine* includes *steam-engines*, *steam turbines*,† *gas turbines*, *petrol-engines*, *oil-engines*, *gas engines*, and also *hot-air engines*.

STEAM-ENGINES

The *steam-engine* is one of the most important machines for converting heat into mechanical work. Steam enters the working-cylinder at a high temperature and pressure, and, after doing work on the piston, leaves the cylinder at a lower temperature and pressure. The difference between the amount of heat-energy in the steam entering and leaving the cylinder represents the amount of energy transformed into work by the steam-engine. Hence, the steam-engine that can take in steam at the highest temperature and let it out at the lowest temperature will be the most efficient, and this is the ideal aimed at by designers of steam-engines. The most efficient steam-engines transform only about 30 per cent. of the heat-energy of their fuel into work, i.e. their thermal efficiency is only 30 per cent. and the other 70 per cent. of the heat-energy is wasted. Most railway steam-engines transform less than 10 per cent. of the heat of their fuel into work, the other 90 per cent. of the heat goes to warm up the atmosphere! Although steam-engines are less efficient than internal-combustion† engines, they are usually cheaper to run on account of the lower price of coal compared with oil fuel, and they can be made in larger sizes than internal-combustion engines.

The necessary steam is produced in the *boiler*, where it collects until a high pressure is reached so that the boiling-point of the water is raised and more heat-energy is stored up in the steam (see p. 43). The boiler is made in such a way that as much as possible of the heat-energy supplied by the burning fuel is given up to the water in the boiler (see Fig. 47).

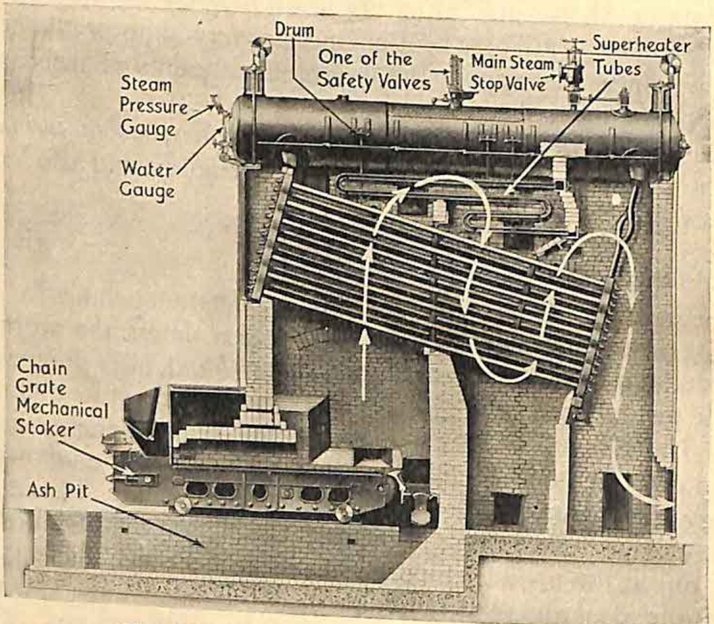


FIG. 47. Babcock and Wilcox water-tube boiler.

This steam passes from the boiler through the *steam-pipe* into the *steam-chest*† which is attached to the *cylinder*. Inside the steam-chest is the *slide-valve*.† In the position shown in Fig. 48, steam enters the cylinder through the right-hand *steam-port*,† and its pressure forces the piston to the left. When the piston nears the other end of the cylinder, the slide-valve moves to the right and closes the right-hand steam-port, thus shutting off steam from the back of the piston. At the same time, the slide-valve uncovers the

left-hand steam-port and admits steam to the front of the piston, besides connecting the right-hand steam-port with the *exhaust-port*.† (See also Fig. 49A.) In this way, steam is admitted first to one side of the piston and then to the other, the slide-valve opening and closing the steam-passages at the proper times. Actually, the steam is cut off when the piston has only completed part of its stroke, making the expansion of the steam push the piston for the rest of the stroke, and thus converting a larger proportion of the energy of the steam into work.

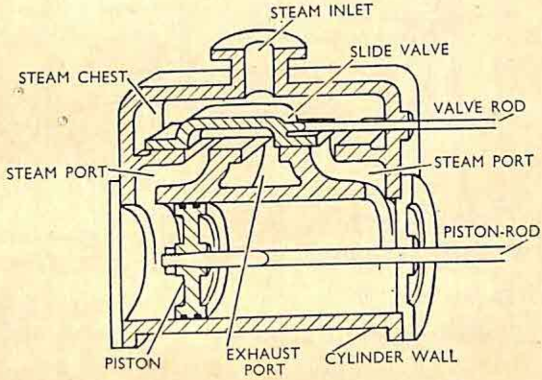


FIG. 48. Section of cylinder and slide-valve.

When the piston is exactly at either end of its stroke, it can exert no turning effect on the crank,† and to carry the engine past these 'dead points', a heavy *fly-wheel*† is used, which keeps the rotation steady.

On each working stroke, the fresh steam has to displace the steam used for the last stroke from the other side of the piston, and this steam has to be pushed out into the atmosphere against a pressure of 14·7 lb. wt. per square inch. If the pressure can be reduced, more useful work can be done by the engine. This back-pressure is reduced by fitting a *condenser*† in which the exhaust steam is condensed by spraying with cold water, thus producing a partial vacuum. If, for example, the pressure in the condenser can

be reduced to 2·7 lb. wt. per square inch, then this is equivalent to an increase in the boiler pressure of 12 lb. wt. per square inch.

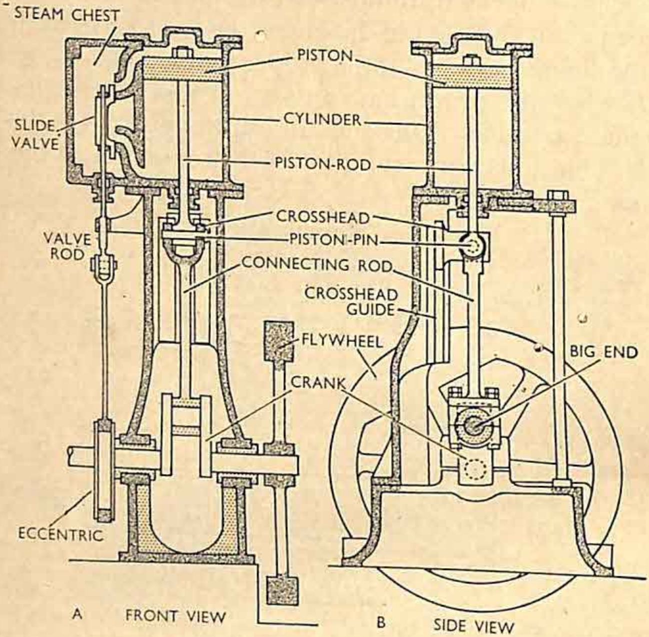


FIG. 49. Slide-valve steam engine.

STEAM TURBINES

The principle of the steam turbine is the same as that of *water-wheels* and *windmills*. A modern turbine has alternate rings of *fixed stator blades* and *revolving rotor blades*, arranged as shown in Fig. 50. The steam is directed by the fixed blades against the revolving blades, causing the latter to revolve. As the steam escapes from one set of revolving blades, its direction is changed by another set of fixed blades so that the steam strikes the next set of revolving blades at the most effective angle.

Turbines are in common use in large ships and in power-stations. They have the following advantages over the ordinary type of

steam-engine: (i) they are more efficient, (ii) they occupy less space for the same power, (iii) there is no to-and-fro movement of heavy pistons, and therefore (iv) they run with much less vibration.

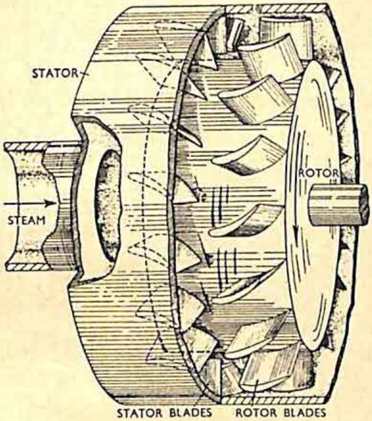


FIG. 50. Principle of steam turbine.

Gas turbines, turbo-jet† engines, and turbo-prop† engines use hot, expanding gases produced from rapidly-burning fuels instead of steam.

THE FOUR-STROKE PETROL-ENGINE

Steam-engines are examples of *external-combustion† engines*, the fuel being burnt *outside* the engine in order to heat the working-substance, e.g. air or steam. An *internal-combustion engine* burns its fuel *inside the cylinder*, and the heat of combustion is converted directly into work without the use of another working-substance.

In the *four-stroke petrol-engine*, the fuel—petrol—is mixed with air in the right proportions to ensure complete combustion of the fuel, this mixture being prepared in the *carburettor*,† as shown in Fig. 51. Such a mixture of petrol-vapour and air explodes when sparked, forming mainly *carbon dioxide* and *steam*; and the force of the explosion drives the piston downwards. In most petrol-engines, *four strokes of the piston* (or two complete revolutions of

the crank-shaft†) are necessary to complete the cycle of operations between each explosion in the cylinder. As shown in Fig. 52, during the *suction stroke* (*a*), the *inlet-valve* IV opens and the piston P

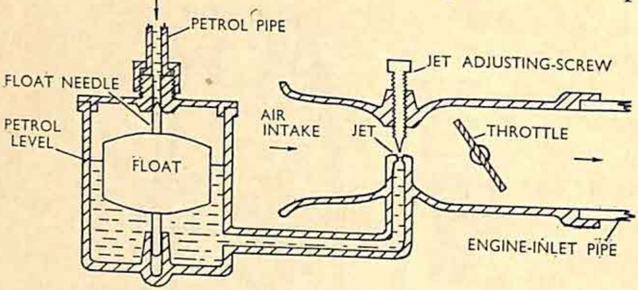


FIG. 51. Simple carburettor.

moves downwards, so that an explosive mixture of petrol-vapour and air enters the cylinder M. As the piston rises at the beginning of the *compression stroke* (*b*), the inlet-valve IV closes and the

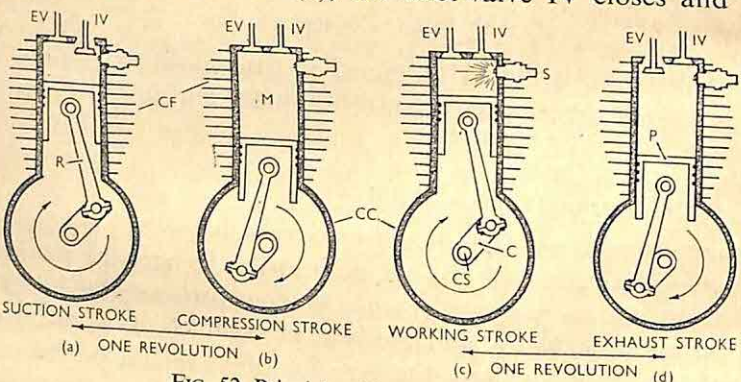


FIG. 52. Principle of four-stroke engine.
C = crank. CC = crank-case. CF = cowling fins. CS = crank-shaft.† S = spark plug.
Remaining letters are explained in text.

charge is compressed into the small space at the top of the cylinder. An electric spark then fires the explosive mixture and the force of the explosion drives the piston downwards on the *working stroke* (*c*). At the beginning of the next upward stroke, the *exhaust stroke* (*d*), the *exhaust-valve* EV opens and the burnt gases are

pushed out into the exhaust-pipe. The engine is now ready to repeat this cycle of four strokes (in two revolutions of the crank-shaft).

Since the engine only receives energy from an explosion during one stroke out of every four, a petrol-engine of this type is fitted with a heavy *fly-wheel* (not shown in Fig. 52) to carry the piston through the other three strokes.

By increasing the number of cylinders in the engine, it is possible to obtain smoother running. Thus a 4-cylinder engine is arranged so that there are two working strokes to each revolution of the crank-shaft; a 6-cylinder engine has three working strokes per revolution, while an 8-cylinder engine has four working strokes per revolution and therefore runs very smoothly indeed.

DIESEL-ENGINES

The *Diesel-engine*† is an internal combustion engine burning heavy oil in the cylinder at a comparatively slow rate, instead of exploding the charge with a spark as in petrol-engines. On the first stroke of a four-stroke Diesel-engine, air alone is drawn in and is then compressed very strongly (to about 500 lb. wt. per square inch) on the second stroke, thus becoming very hot indeed. A fine spray of fuel oil is then forced into the hot cylinder and begins to burn at once, continuing to burn during the first part of the working stroke (see Fig. 53).

On the fourth stroke the burnt gases are pushed out through the exhaust valve. No electric spark is needed to fire the charge, but the charge burns smoothly, without a sudden explosion, thus exerting a steady pressure on the piston throughout the working stroke. The Diesel-engine has the great advantage of using a relatively cheap fuel, 'heavy' oil, and it converts more heat into work than any other heat-engine. The fuel is not readily inflammable*—a great advantage over highly-inflammable petrol.

THE THERMAL EFFICIENCY OF HEAT-ENGINES

We have seen that it is possible to transform mechanical energy completely into an equivalent amount of heat-energy (as in Joule's

experiments). Although the reverse change of heat-energy into mechanical energy is theoretically possible, it is impossible to carry out in practice since the exhaust-steam or burnt gases still contain

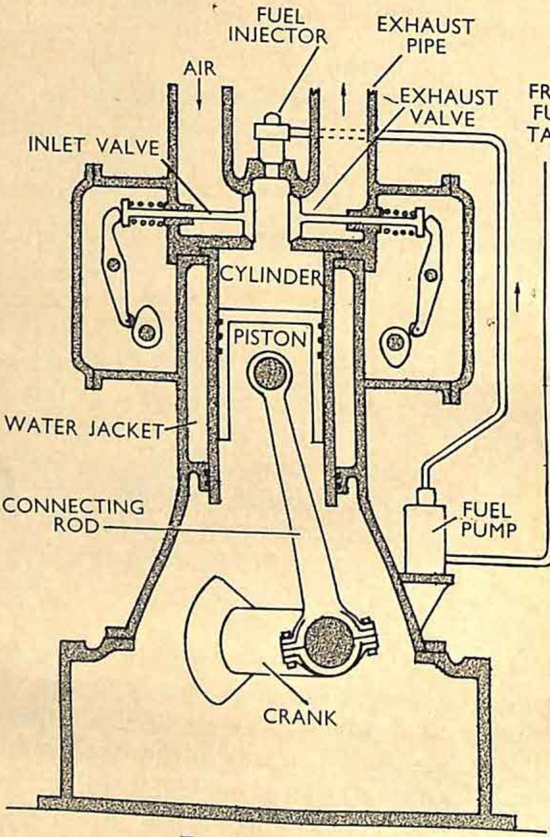


FIG. 53. Diesel-engine.

heat when they escape from the engine, and for this reason all heat-engines are very wasteful of energy. The thermal efficiency of a machine is defined as

$$\text{THERMAL EFFICIENCY} = \frac{\text{USEFUL ENERGY OBTAINED FROM MACHINE}}{\text{HEAT ENERGY PUT INTO MACHINE BY BURNING FUEL}}$$

and this is usually expressed as a percentage. The most efficient internal-combustion engines (Diesel-engines) convert only about 33 per cent. of the heat-energy of the fuel into mechanical work.

REVERSED HEAT-ENGINES—COOLING MACHINES

The machine described below depends for its action upon work done against molecular forces. It is typical of the refrigerating machines used for ice making, cold storage, and 'air-conditioning'.

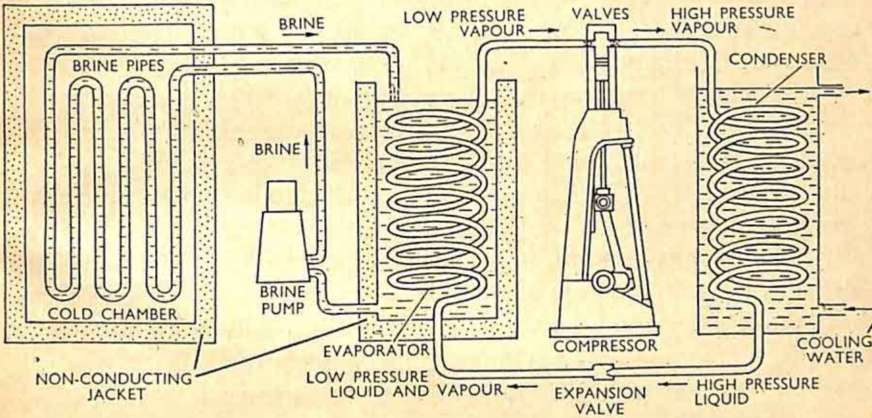


FIG. 54. A cooling machine.

The commonest type of refrigerating machine (see Fig. 54) consists of a *compression-pump*, a *condenser*, an *expansion-valve*, and an *evaporator* through all of which the working-fluid circulates. This working-fluid is a gas that is easily liquefied by pressure and moderate cooling. Carbon dioxide is used on board ships, ammonia in ice-making factories, and sulphur dioxide in household refrigerators (although, in the latter, sulphur dioxide is now being replaced by non-poisonous organic compounds). The compression-pump, driven by a heat-engine in large machines and by an electric motor in small ones, compresses the gas and so raises its temperature. Thus part of the work done *on* the gas is converted into heat, which is then removed from the gas as it passes through the coiled

tubes of the condenser (cooled by air or water). The compressed gas liquefies on cooling, giving up its latent heat of evaporation as it condenses. The liquid, which is under a high pressure in the condenser, then escapes through a very small opening in the expansion-valve into the coiled tubes of the evaporator, where the pressure is low, so the liquid immediately evaporates and the vapour expands. In evaporating, the liquid takes its latent heat of evaporation from the evaporator and its surroundings, and the sudden expansion of the gas increases this cooling effect. Finally, this low-pressure gas returns to the pump and is compressed for a new cycle of changes.

In domestic *compression-type* refrigerators, the compression-pump is usually driven by a small electric motor. In homes out of reach of public electricity supplies, the *absorption-type* refrigerator can be used. This has no machinery with moving parts, since its working depends only on the fact that cold water dissolves many times its own volume of ammonia gas, but the ammonia is easily driven off again by heat (supplied by a small oil-lamp). This free ammonia gas passes into condensing coils where it is liquefied. The liquid ammonia then flows into evaporating coils, where it evaporates very rapidly, absorbing the necessary latent heat of vaporization from inside the refrigerator, which is therefore cooled. The gaseous ammonia then returns to the absorber and dissolves in water once more, thus completing the cycle of changes. These absorption-type refrigerators also have 'heat-exchangers' and 'cold-exchangers' which make them more efficient but more com-
plicated. In this General Science Course, however, we can only
outline the basic principle of these absorption-type refrigerators.

HEAT-ENERGY AND CHEMICAL ENERGY

We have seen that heat is a form of energy and that it can be
changed into mechanical energy. There is also a similar relation-
ship between heat-energy and *chemical energy*. We know that
when wood or coal is oxidized (or burnt) and when sugar is
respired (in a living organism) energy is set free from the chemical

compounds. Some of this energy may be changed into *mechanical energy*, e.g. when the machines or organisms *do work*. Some of it, however, appears as *heat*. When chemical reactions take place, heat is often given out (though sometimes heat is absorbed, so that the reacting substances become cooler). Quite apart from this liberation or absorption of heat, we usually find that chemical reactions are speeded up when the reacting substances are heated and, as a general rule, the rate of a chemical reaction is doubled by a rise in temperature of 10° C. This is why all laboratories are fitted with Bunsen burners, so that substances can be made to react together more quickly, thus reducing the time taken for our experiments.

HEAT AND LIVING THINGS

In general, plants and animals can live only within a narrow range of temperatures (roughly from 0° C. to 50° C.). The living substance, *protoplasm*, is very sensitive to changes in temperature. Chemical reactions in it go on faster at higher temperatures within this range, but if the temperature rises above about 50° C. the protoplasm is destroyed and the organism dies. Most living organisms, also, are killed by temperatures lower than 0° C. Here the effect is not so much the cold (the first result of which is the slowing down of chemical reactions in the protoplasm) as the damage caused to the delicate cells when ice forms inside them.

Dry *seeds* and some bacterial *spores*, in which the percentage of water is low and the protoplasm is not active, can withstand quite high temperatures (e.g. 110° C. for four hours in the case of many seeds) without injury,* and may even be kept in liquid oxygen (at − 183° C.) for some time without damage. But once these seeds or spores have taken up water and have begun to grow they lose their resistance to extremes of temperature.

Milk and other foods go bad quickly in hot countries because the high temperature increases the rate of growth and reproduction of the bacteria and fungi that cause decay. *Pasteurization* [1]† and

[1] Heating milk to not less than 142° F. for 30 min. (or to 162° F. for 15 sec.).

boiling of milk, and *heat sterilization** of bottled and canned foods are not always efficient in preventing decay because the temperatures used may not be high enough to kill the *resting* spores. In bacteriological laboratories and in hospitals, equipment is usually *sterilized* by heating it while damp to temperatures of about 120° C. (see Book IIIA, Chap. 8). Another way in which food can be preserved is by *refrigeration*. This does not *kill* the bacteria, but their growth rate is slowed down sufficiently to prevent them from multiplying and doing any serious harm.

Temperature has a marked effect on the growth of plants. Outside the tropics, plant growth slows down during the winter and may stop altogether until spring brings a rise in temperature. This increased rate of growth is mainly due to the effect of higher temperatures on the many chemical and physical processes going on in plants, e.g. intake of water, manufacture of new protoplasm, respiration.

Green leaves are freely exposed to radiant heat-energy from the Sun and their temperature tends to rise during the daytime because they absorb this heat and also because much of the light energy they absorb is converted into heat (the remainder being converted into chemical energy during photosynthesis). The leaves, however, lose a lot of this heat by *radiation* to their surroundings and by *convection* currents in the air. They are also cooled by *transpiration* (see Book Two, Chap. V). As the combined result of all these heat losses, the temperature inside a leaf is usually only a degree or two above that of the surrounding air.

(See *General Science Workbook*, Book Two, pp. 1–38, for learning exercises on this chapter.)

CHAPTER II

LIVING THINGS—THE HIGHER ANIMALS

Our earlier studies of plant life were all based on *flowering plants*, sometimes called the 'higher [1] plants' because they are better adapted to life on land than are the 'lower plants', e.g. seaweeds, fungi, mosses, and ferns. For this reason the flowering plants have become the dominant* plants on the Earth's surface.

In the same way, now that we are beginning to study animals, we shall base our early work on the 'higher animals'. The 'highest' animal of all is *Man*, and we are naturally more interested in our own bodies than in those of 'lower' animals. But when we come to study internal structure it will be much more convenient to work on some smaller animal that is built on the same general plan. We shall use, therefore, the guinea-pig,† which belongs to the same 'class' of animals—the *mammals*.† (Rabbits† or rats will serve equally well for dissection.)

THE HUMAN ANIMAL

From the scientific point of view, Man is an *animal*, with a body built on the same general plan as all the other members of that great class of animals called *mammals*, and when we come to study the internal structure of the human body it will often be instructive to examine the corresponding parts in a dissection of one of the smaller mammals.

The mammals form a large group of animals, including most of the common four-footed animals of everyday life, e.g. dogs and cats, rats and mice, horses and cows, sheep and goats,† monkeys† and men. There are also a few mammals that live in water—whales, porpoises,† seals†—and the bats, which can fly. All the mammals

[1] 'Higher' also means 'appearing later in the fossil records of the rocks.'

have in common that their young are fed with milk by the mother-animal, which has *mammary*† *glands* for this purpose. Most mammals also have other characteristics, e.g. (*a*) The skin is hairy; (*b*) They have external ears; (*c*) They grow more or less permanent teeth, sunk in sockets* in the jaw-bones (these teeth being of different kinds, suitable for cutting, tearing, and grinding food); (*d*) They are 'warm-blooded', i.e. they can keep their inner body-temperature always the same, no matter whether their surroundings are hot or cold; (*e*) They have a *diaphragm*† dividing the body-cavity into two smaller cavities, one containing the four-chambered heart and the lungs; the other containing most of the organs concerned with digestion of food, with reproduction, and with excretion† of urine.

In nearly all mammals, the young ones grow from an egg while still inside the mother-animal, and the young are fairly fully developed when they pass out from the mother's body at birth. Some are at first blind and helpless (e.g. new-born kittens*), while others (e.g. calves*) are able to look after themselves very soon after birth. The human baby is the most helpless of all young mammals and needs years of *parental care*. We can classify mammals in another way—according to the food they eat. A very large number are *herbivorous*† or *plant-eating animals*; many of these live in herds when in the wild state and depend on their running-powers to escape from their enemies. Some other mammals are *carnivorous*† or *flesh-eating animals*; these are hunters, living on the flesh of smaller or weaker animals. A few mammals, like Man, are *omnivorous*,† feeding on both plants and animals.

Man is a mammal of a special kind. With the monkeys and the apes† he forms a sub-group called the *primates*,† mammals with large brains, useful grasping* hands, and clear-seeing eyes. Man is distinguished from most other mammals by his upright position when walking and by his very large brain, but he has the same essential needs and his body works in much the same way as any other 'higher' animal. So we can learn a lot about Man by studying other mammals, e.g. by dissecting a rabbit or a rat (as

described on pp. 299–304) we can get a very good idea of what we ourselves are like inside.

THE BODY-REGIONS OF A MAMMAL

There are four distinct body-regions in most mammals: (i) the head, (ii) the neck, (iii) the trunk,* and (iv) the tail. The neck is not clearly marked off, however, in whales and seals, mammals that live in water. The tail, also, is sometimes very short, as in rabbits and bears,† or almost absent, as in guinea-pigs and men.

The Head. The head carries the animal's most important *sense-organs* (eyes, ears, and nose). In fact, the head is that part of the body which explores the unknown and puts the animal in touch with its surroundings. The head is clearly the best place for the sense-organs and for the mouth—on that part of the body which usually goes in front.

The Neck. The neck joins the head to the trunk. It enables the animal to turn its head without turning the rest of its body. (An animal without a neck, e.g. a frog, has to turn its whole body in order to look in a new direction.)

The Trunk. This forms the largest part of the body. In mammals, it is divided into two parts: (*a*) the *thorax*,† or chest, surrounded by the *ribs* and *diaphragm* and containing the *lungs* and *heart*; and (*b*) the *abdomen*,† or belly-cavity,† enclosed in which are most of the body-parts concerned with digestion of food, with reproduction and with excretion of urine.

The Tail. In some mammals, e.g. kangaroos,† mice, and some monkeys, the tail is used for balancing or for climbing; but in other mammals, e.g. Man, it is very short and may not even project* from the surface of the body.

The Limbs. There are two pairs of limbs attached to the trunk: (*a*) a pair of *fore*-limbs*, and (*b*) a pair of *hind*-limbs*. The limbs are used as jointed levers to enable the animal to move about.

AN OUTLINE OF HOW HIGHER ANIMALS LIVE

The first need of any animal is a sufficient supply of suitable food, which is used partly in building and repairing its body, and

partly as a source of energy. For during the growth of the animal and the formation of the complex chemical substances of which it is made, in movement and in keeping warm, the animal uses *energy*. A living thing cannot *create* energy, but it can *transform* energy from one form to another. Living things, like machines, can be looked upon as *energy-transformers*. Green plants get energy, in the first place, from the Sun, the *chlorophyll*† (or *leaf-green*) absorbing that part of sunlight which supplies the energy necessary for *photo-synthesis*. During photo-synthesis, the green plant changes this light energy into *chemical energy*, stored up in the form of manufactured food. Animals cannot make this food themselves (i.e. they cannot photo-synthesize), but they get their food from plants or from other animals that have fed on plants. *All the energy used by living things, then, comes in the first place from the Sun, and the most important difference between animals and plants is that animals cannot transform the energy of sunlight into chemical energy.*

One of the most striking things about animals and plants is the way in which they are fitted or adapted to the surroundings in which they live (i.e. their *environment**). For instance, a green plant gets the raw materials for making its food from the soil and from the air, and we find that it is firmly rooted in the soil and exposes its leaves to air and sunlight. On the other hand, animals eat solid foods of various kinds and they drink liquids; and they have compact* bodies. In finding their food they use *sense-organs*, and most higher animals move towards their food, using the pull of *muscles* on the jointed bones of their limbs, which act as levers. (The framework of *bones*, or *skeleton*, also serves to protect certain parts of the body.)

An animal is also adapted to deal with the food that it eats, both in its *structure* (the way it is made) and in its *physiology* (the way it works). The food is taken, through the mouth, into the *food-canal* (or *alimentary*† *canal*). A good deal of the food eaten is not soluble in water, but once inside the food-canal it is broken down, or *digested*, into simpler, soluble substances, which can move easily

through the walls of the food-canal into the *vascular system*. The *blood*, which fills this system, carries the dissolved food material round the body to the parts where it is used. Some of the food is used in building up new parts or in repairing worn parts of the body, but much of it is *oxidized* in the process of *respiration* and the energy thus set free is used in movement and growth, or it appears as heat.

The higher animal requires air, from which it obtains the oxygen used in respiration. Many aquatic* animals, e.g. fishes, use the oxygen dissolved in the water in which they live. The higher animals mostly live in air and are covered with a skin, often hairy, through which oxygen cannot easily pass. An adaptation to land life is here seen in the possession of *lungs*, a breathing system and an oxygen-transporting system. The mammal takes air into its lungs (inside the chest), and from these the oxygen is carried by the blood to those places where oxidation goes on. The blood also carries the waste substances produced by the body; one of these, carbon dioxide, is lost through the lungs, others leave the body in solution by way of the *kidneys*,† while a good deal of water is given off through the skin as *sweat*.

It is clear, then, that in the body of a higher animal many different things are taking place at the same time. If the body-machine is to work smoothly, all these activities—muscle movements, digestion of food, transport of food materials, oxygen and waste products—must be kept exactly in step with each other. These processes are delicately controlled by the brain† and the *nerves*†, and by *hormones*[1]†. The special *sense-organs*, e.g. eye and ear, keep the animal informed of what is happening around it.

This briefly summarizes how the body-machine of the higher animal works, but there is one point more that applies to all living things. An animal's body cannot go on working for ever; sooner or later it 'wears out' and death takes place. Animals (like plants), however, have the power of *reproduction*, and before they themselves die, they usually bring into existence a new generation.*

[1] Hormones will be discussed in Book Four.

The striking difference in the structure and appearance of plants and animals reflects the fundamental* difference between their methods of feeding. *Plant nutrients* [1] are present almost everywhere—carbon dioxide is in the air, and water, containing dissolved mineral salts, is in the soil. A plant, therefore, does not need to move about from place to place in search of nutrients (although it may have to search for sufficient light). A typical plant is fixed to one spot and develops as large an absorbing surface as possible; on thin, flat leaves, exposed to air and sunlight by the spreading branches, and on roots running through the surrounding soil in all directions. The typical animal is built on a more compact plan because it finds its food ready-made and because it is not surrounded by suitable raw materials for its food, as a plant is.

Having found its food, an animal eats it and it is then passed from the mouth into the *food-canal*.† Here the solid food is *digested*, i.e. broken down into simpler substances that are capable of *diffusing* through a thin skin or membrane* into the bloodstream.

THE FOOD-CANAL

Animal food must contain *carbohydrates*, *fats*, and *proteins*, *water*, *mineral salts*, and *vitamins*,† and we shall learn more about these in Book Four. For the present, it will be sufficient to know a few common examples of each group.

The commonest *carbohydrates* used for food are *starch* and *sugar*; rice, potatoes, and wheat-flour are starchy foods. Common sources of *fat* are meat-fat, butter, milk, egg-yolk,* nuts, and vegetable oils. *Protein* is supplied by lean meat, white-of-egg, milk, and seeds (especially peas, beans, and lentils). You should also remember that *although carbohydrates, fats, and proteins can all be*

[1] Strictly speaking, carbon dioxide, water, and mineral salts are not *foods* (for they do not supply *energy*): so we call them *plant nutrients*† or the *raw materials of plant food.*

used to supply the animal with energy, only proteins can be used for body-building, i.e. *for growth, repair, and reproduction.*

Man, like other mammals, takes in food at the mouth, with the aid of the lips and teeth. If the solid food is too large to go in the mouth, smaller pieces are bitten off by the front, or cutting, teeth. This food is then *chewed*,* i.e. ground up by the back teeth and worked into a ball ready for swallowing. While the teeth are tearing and grinding the food, it is moistened and softened by *saliva*,† a digestive juice, which is poured into the mouth from the *salivary glands*.† In Man, two pairs of these lie between the tongue and the lower jaw while a third pair lies to the outside of the lower jaw-bone just below the ear. (These are the glands that become infected and swollen when we get *mumps*.†) The saliva contains an *enzyme*† that helps to break down *starch* in the food into soluble sugars. Thus, digestion begins in the mouth. The food is swallowed, i.e. passed down the *gullet*† (or *oesophagus*),† which leads down inside the animal's neck and through the chest cavity to the *stomach* (see Fig. 55).

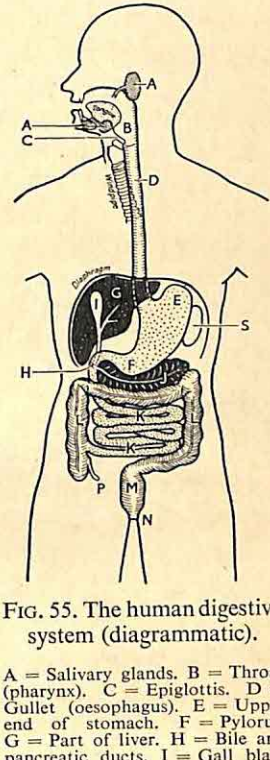


FIG. 55. The human digestive system (diagrammatic).

A = Salivary glands. B = Throat (pharynx). C = Epiglottis. D = Gullet (oesophagus). E = Upper end of stomach. F = Pylorus. G = Part of liver. H = Bile and pancreatic ducts. I = Gall bladder. J = Pancreas. K = Small intestine. L = Large intestine. M = Rectum. N = Canal to anus. P = Appendix. S = Spleen (not concerned with digestion).

The *wind-pipe*,† leading to the lungs, also opens into the back of the mouth, near the upper end of the gullet, and if food gets into the wind-pipe through this opening (the *glottis*†), it is likely to cause choking. Such an accident is rare, partly because, during swallowing, the muscles at the top of the wind-pipe close the tube, partly because a small flap*-like projection; the *epiglottis*,† directs food away from the glottis during swallowing (see Fig. 56).

As soon as food is inside the gullet, it passes beyond *conscious* control. It does not, however, *fall* down the gullet, but it is forced down by a series of muscular movements in the walls of the food-tube. Thus it is possible for most mammals (e.g. cattle) to eat with the head held below the trunk. The muscles of the gullet contract behind and relax* in front of the food-ball and thus push it quickly down into the stomach. These *involuntary** movements of the wall of the food-canal are known as *peristalsis*† (see Fig. 57).

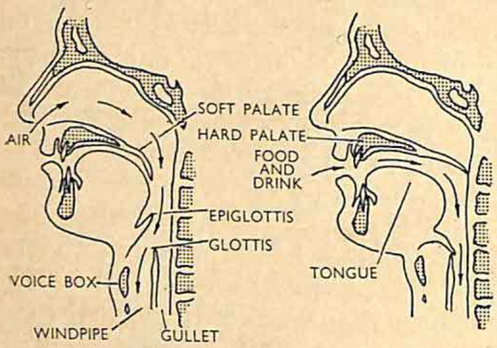


FIG. 56. Breathing and swallowing.

The *stomach* is a large muscular bag (situated immediately below the *diaphragm*), which holds the food for some hours while a digestive juice (the *gastric*† *juice*) acts upon it. During this stage in digestion the walls of the stomach move in such a way as to mix their contents thoroughly with the gastric juice. Afterwards the partly digested contents are squirted, a little at a time, into the *small intestine*,† a long, narrow tube folded into many loops. (In Man, the small intestine is about 22 ft. long [1] and 1 in. in diameter, i.e. it is only 'small' in diameter by comparison with the diameter of the large intestine.) In the small intestine, the partly digested food meets two more digestive juices, *bile*† (from the *liver*†) and *pan-*

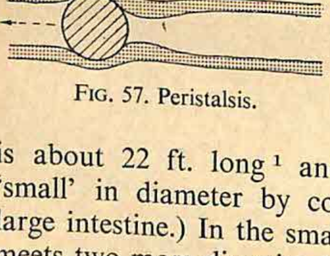


FIG. 57. Peristalsis.

[1] This is the average length; in some individuals the small intestine may be as short as 16 ft. and in others it may be as long as 25 ft.

creatic juice† (from the *pancreas*),† which carry digestion a stage further. Digestion is completed by the *intestinal juice*† (from the walls of the small intestine), so that the digestible portion of the original solid food is now changed into simpler, soluble, and diffusible substances. This digested food is *absorbed* through the walls of the small intestine and is dissolved by the blood in the tiny blood-vessels running through these intestinal walls.

From the small intestine, the undigested and unabsorbed remains of the original food pass on to the *large intestine*† in a very liquid state, and in this part of the food-canal water is absorbed, so that the waste material is reduced to about one-tenth of its former volume. It then passes through the *rectum*† to the *anus*,† where it is got rid of as *faeces*.† The food-canal, therefore, is a digestive tube running from the mouth to the anus, open to the external world at its two ends. The lower part of the food-canal (the large and small intestines) is sometimes called the *gut*.†

This is a broad outline of the process of digestion. In Book Four we shall learn how digested and absorbed food gets to the parts of the body where it is used.

Note. When you examine a dissected mammal (p. 301), you will find that the various parts of the food-canal do not lie free in the body-cavity, but that they are suspended in folds of thin and more or less transparent membrane (called the *peritoneum*).† This membrane lines the body-cavity and also extends over the food-canal, which is suspended in a fold of the peritoneum called the *mesentery*.† In the mesentery lie the blood-vessels supplying the food-canal.

GETTING OXYGEN—BREATHING

On p. 90 we learnt that *all living things use energy* and that they get the necessary energy from their food. This process, during which food is oxidized and its chemical energy transformed into useful forms, is called *respiration*. This process involves taking

in oxygen and giving out carbon dioxide, and it goes on in all living things, though usually more rapidly in animals than in plants. In its full modern sense, *the scientific term 'respiration' means the whole process of transforming energy by breaking down complex chemical compounds into simpler ones possessing less chemical energy*. Some of the energy is liberated as *heat*; the rest is used in growth, repair, and movement.

Respiration involves the use of oxygen. *Plants* expose a large surface to the air and exchanges of oxygen and carbon dioxide take place over nearly the whole surface of the plant. Gases pass in and out of the tiny openings (stomates and lenticels) very readily by diffusion and they enter or leave the living plant cells by the same process. In the 'higher' *animals*, on the other hand, the body is very compact (i.e. the surface area is small compared with the total volume of the animal) and there are no openings in the skin comparable to stomates. In Man and all the other 'higher' animals, the exchange of oxygen and carbon dioxide with the air takes place in one region only—the *lungs*—and not over the whole surface of the body. The air in the lungs is constantly renewed by the process we call *breathing*—which is quite distinct from respiration proper. In mammals, breathing means the alternate taking-in of a quantity of air into the lungs and the pushing-out of a gas poorer in oxygen and richer in carbon dioxide.

THE LUNGS

In Man and other mammals, the two lungs are soft, spongy* bodies (see Fig. 58), lying in cavities of the chest. These *pleural cavities*† are lined by a very thin *pleural membrane*,† a fold of which, in each cavity, surrounds the lung, which therefore lies in a double-walled sac.* A very thin layer of fluid in these *pleural sacs*† helps to protect the lungs from damage by friction. The *ribs* and muscles enclose the top and sides of the chest-cavity, while its floor is formed by the *diaphragm*, a curved sheet of tough fibre with muscle round the edge, which separates the chest-cavity from the rest of the body-cavity (see Fig. 58). In this way, the lungs are

enclosed in an air-tight chamber, which they always fill completely during life, and whose only opening to the outside world is through the wind-pipe. (This is seen clearly during the dissection of a mammal; if a small hole is made into the pleural cavity, air enters, the pressure inside and outside the lungs is equalized and, because the walls of the lungs are *elastic*, they now contract and the lung collapses.*)

This observation should help you to understand the way in which you breathe. We say that, when we breathe, we 'suck' air

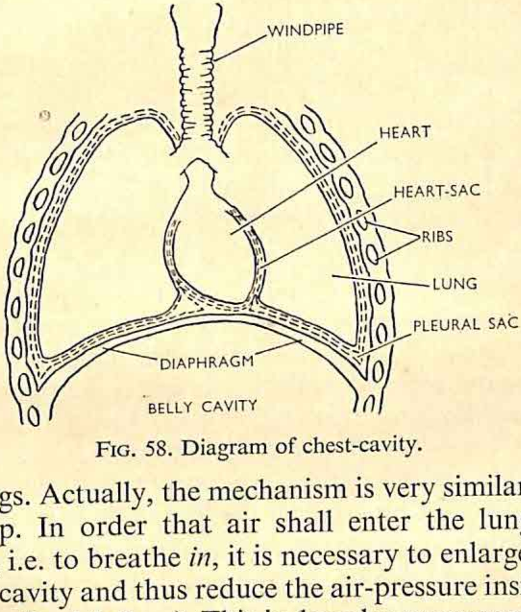


FIG. 58. Diagram of chest-cavity.

into our lungs. Actually, the mechanism is very similar to that of a bicycle-pump. In order that air shall enter the lungs from the atmosphere, i.e. to breathe *in*, it is necessary to enlarge the volume of the chest-cavity and thus reduce the air-pressure inside the lungs (according to Boyle's Law). This is done by movements of the ribs and diaphragm. Some of the powerful muscles attached to the ribs contract and pull the ribs upwards and outwards, thus increasing the size of the chest-cavity all round. At the same time, the centre of the diaphragm is pulled downwards as the muscles around its margin contract, thus increasing the size of the chest-cavity still further. This increase in volume of the air-tight chest-cavity causes

a reduced pressure inside the lungs, and *the air is forced down the wind-pipe by the pressure of the atmosphere outside*, until the air-pressure inside the lungs becomes the same as that of the outside atmosphere (see Fig. 59).

'Breathing-out' takes place when the muscles of the ribs and diaphragm relax and allow these parts to return to their original positions, thus forcing air out of the lungs through the wind-pipe.

In passing from the atmosphere into the lungs, the air first enters

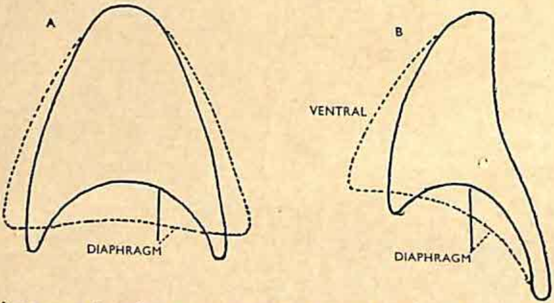
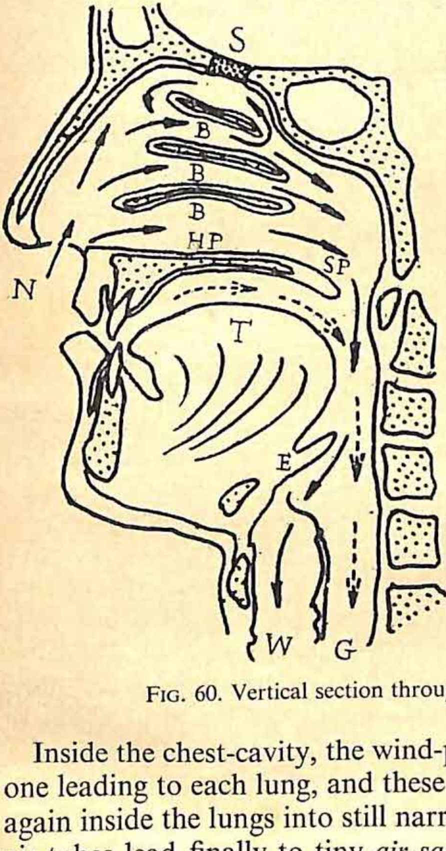


FIG. 59. Diagrams showing movements of chest-wall and diaphragm during breathing.
A = front view. B = side view. (*After Grove and Newell.*)

the *nostrils* (see Fig. 60) where it passes through a winding passage whose walls are covered with a sticky liquid (*mucus*†). Under natural conditions, any dust or dirt is caught by this sticky liquid and by hairs that grow in the entrance to the nose. At the same time, if the outside air is dry, it will become moistened with water vapour as it passes through the nostrils, and there will be no danger of drying up the delicate absorbing surfaces inside the lungs. Besides this, if the outside air is cold, it is warmed to about the same temperature as the blood when it travels through the winding passages in the nose, and this removes the danger of suddenly cooling the lungs. To sum up, *the air is filtered, moistened, and warmed in passing through the nose*. (*N.B.* The mouth has these safeguards* less highly developed; hence 'mouth-breathing' is a bad habit.)

From the nose, the air passes down the back of the mouth-

cavity into the *wind-pipe* (or *trachea*),† which leads down through the neck into the lungs. The walls of the wind-pipe, also, are covered with mucus that is continually moving upwards towards the throat, carrying with it any dust that was not trapped in the nose.



Dotted arrows show path of food and drink. Black arrows show path of inspired air. N = nostril. B = curved bones. E = epiglottis. G = gullet. HP = hard palate. SP = soft palate. S = sense organ of smell. T = tongue. W = wind-pipes.

FIG. 60. Vertical section through head (diagrammatic).

Inside the chest-cavity, the wind-pipe divides into two branches, one leading to each lung, and these branch tubes divide again and again inside the lungs into still narrower air-tubes. These very fine air-tubes lead finally to tiny *air-sacs*† (see Fig. 61) and it is here that the actual exchange of gases between blood and air takes place. The total area of all these tiny air-sacs is enormous: it has been estimated that if all the air-sacs in a man's lungs could be

spread out flat, they would cover a total area of over 100 square yards, i.e. about a hundred times more than the total area of his skin. Hence, although a mammal has a compact body with a relatively small surface area, the structure of the lungs provides, inside the chest-cavity, a very large surface through which oxygen is absorbed into the blood-stream.

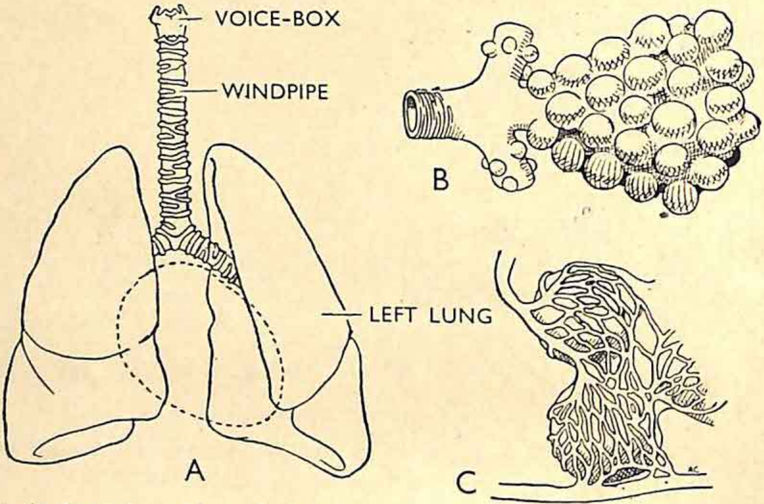


FIG. 61. A: the lungs (dotted line shows position of heart). B: end of air-tube showing air-sacs (magnified). C: air-sacs surrounded by blood-capillaries (more highly magnified). (*After Holmes and Gibbs.*)

The two models shown in Figs. 62 and 63 illustrate the way in which we breathe. (i) The bell-jar shown in Fig. 62 represents the chest-walls, and the rubber sheet tied across the mouth of the bell-jar represents the diaphragm. The rubber balloon represents one lung, and the glass tube represents the wind-pipe. On pulling down the 'diaphragm', the 'lung' fills with air. On pushing up the 'diaphragm', the 'lung' empties. This model, of course, only illustrates the action of the diaphragm during breathing; it does not show the part played by the ribs. (ii) The jointed framework shown in Fig. 63 represents two ribs attached to the backbone† at one

end and to the breastbone† at the other end. The rubber bands represent some of the muscles between the ribs. As one set of 'muscles' contracts, the other set relaxes and the 'ribs' are lifted upwards and outwards; this enlarges the chest-cavity. When this muscle action is reversed, the 'ribs' and 'breastbone' return to their original positions (see also Fig. 59).

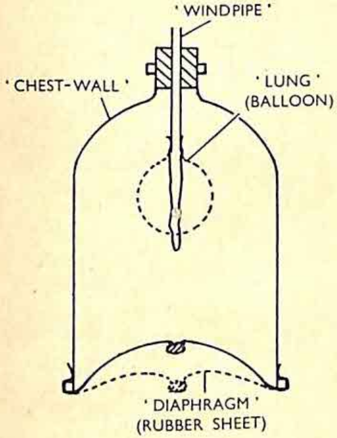


FIG. 62. Model showing action of diaphragm in breathing.

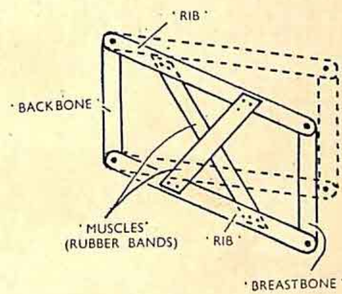


FIG. 63. Model showing action of ribs in breathing.

THE TRANSPORT OF FOOD AND OXYGEN IN THE BODY

We have now briefly described how soluble, diffusible foods are formed in the intestine during digestion, and how the air in the lungs is constantly renewed during the movements of breathing. Now the actual oxidation of food and the building-up of new materials go on in the individual living *cells* of every part of the body. In mammals there is a very complex system that transports food from the intestine to these body-cells and also carries to them oxygen from the lungs. The same system removes waste products from the cells and also helps to equalize the temperature of the body. It is called the *vascular system* and the liquid that acts as the transporting agent is the *blood*.

THE VASCULAR SYSTEM

The blood is carried in a complicated network of *blood-vessels*, which together form the vascular system. This differs from the vascular system in plants (which also carries water and food materials) in that it is a 'closed' system, the tubes of which it is made being all connected together to form a closed network of blood-vessels. Water, gases, and other chemical substances, however, can and do pass easily into and out of this 'closed' system through the thin walls of the *capillary blood-vessels*.

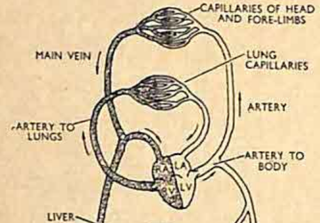


FIG. 64. Blood system of mammal (diagrammatic).
(Oxygenated blood unshaded; de-oxygenated blood shaded.)

In the higher animals, the vascular system always consists of (*a*) a *heart*, (*b*) *arteries*,† (*c*) *veins*, (*d*) *capillaries*. The heart is a muscular pump that forces the blood round the body *away* from the heart along the arteries. The veins are the blood-vessels that carry the blood *towards* the heart. The capillaries are very fine blood-vessels that join arteries to veins and bring the blood close to the living body-cells.

The heart, which in Man is about the size of a closed fist,* lies inside the chest-cavity, between the lungs. It is enclosed in a thin double-walled sac, the *pericardium*† (see Fig. 58), and we may regard the heart simply as two muscular pumps lying side by side, each with two compartments.* The left heart-pump (see Fig. 64) receives the 'fresh' blood (i.e. blood rich in oxygen) from the lungs and pumps it to all the other parts of the body. The blood returns from these organs poor in oxygen and rich in carbon dioxide, and passes to the right heart-pump, which sends it round through the lungs to the left heart-pump again. In its passage through the *lungs* the blood loses carbon dioxide and takes up a

fresh supply of oxygen. In its passage around the *body* the blood loses oxygen (which is used in oxidation) and takes up dissolved food and the waste product carbon dioxide. The right heart-pump is only concerned with sending blood to the lungs, while the left heart-pump is concerned with sending blood to the rest of the body.

(*Important Note*. When describing parts of an animal as 'left' or 'right', imagine yourself to be standing behind the animal and looking towards its head (or imagine yourself in the animal's place). Since Man stands upright on his hind limbs, with his backbone vertical, while most other mammals stand on all four limbs with their backbone horizontal, the terms 'back' or 'front' may be very confusing. In describing the position of the parts of *any* animal's body, therefore, we use the terms *anterior*† (= 'towards the head'), *posterior*† (= 'away from the head'), *dorsal*† (= 'on or near the back'), *ventral*† (= 'towards the belly-surface' or 'away from the back'). In books describing the structure of Man in particular, the terms 'superior'† or 'inferior'† are substituted* for 'anterior' and 'posterior', but for the ordinary educated citizen it is simpler to use one set of terms that will apply to all the higher animals rather than learn a special system for one particular animal—Man. You will notice that in Figs. 55, 58, and 66 the organs are drawn as they would appear in a dissection, i.e. as seen from the ventral side. The right-hand organs therefore appear on the left of the diagram.)

The heart of an adult* man at rest beats about 70–80 times a minute. Each 'beat' consists of the emptying of the four chambers of the heart, followed by their filling while the heart muscles rest for a short interval. The heart-beat can be felt just below the fifth rib on the left side of the chest, because at each contraction the left heart-pump presses against the chest wall at this point. The heart-beat can also be counted by feeling the *pulse*,† which is the wave of pressure that passes down the arteries following each contraction of the heart-pump. The pulse may be felt wherever an artery comes close to the surface of the body, and especially when it is backed by bone as at the wrist and temple* or inside the elbow and ankle.*

(1) Feel the pulse in the left wrist. Place the right hand with the palm pressing against the back of the left wrist and bend the fingers round until the pads of the first and second fingers lie on the wrist just above the ball of the thumb. The pulse may be safely stopped (for a short time) if you get someone to press on the artery that runs along the inside of the left arm just above the elbow.

(2) After counting the pulse, do some vigorous exercise for 30 seconds, e.g. 'knees up' or skipping.* Then count the pulse again and notice that exercise increases the rate of the heart-beat; this

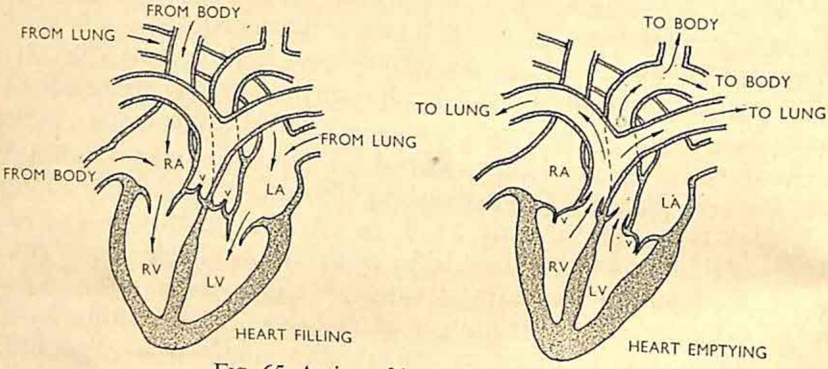


FIG. 65. Action of heart (diagrammatic).

RA = right auricle. LA = left auricle.
RV = right ventricle. LV = left ventricle.
V = valves (in closed positions).

is reflected in the increased rate and greater 'bounce'* of the pulse.

When the left heart-pump forces blood into the main artery (or *aorta*)† and thence to the arteries, these tubes are stretched, but their walls are elastic and between the heart-beats they continue to squeeze blood along the tubes in a direction *away* from the heart, because the walls tend to return to their original position and the *valves* of the heart prevent back-flow (see Fig. 65). Thus a fairly high blood pressure is kept up in the arteries, and this is increased for a time after each fresh contraction of the heart-pump. When a man of average size is at rest, his left heart-pump delivers

about $2\frac{1}{2}$ pints of blood per minute. The total amount of blood in a man's body is about 10 pints.

Most arteries run well below the surface of the body, and they are only damaged by deep wounds. If an artery is cut (*a*) the blood rushes out from the wound in a series of jerks or pulses, (*b*) it is bright red, and (*c*) the flow may be stopped if pressure is applied to the artery or flesh on the side of the wound that is *nearer to the heart*. When a large artery is cut, an animal is in serious danger of bleeding to death unless such pressure can be quickly applied. The blood in the large arteries is pumped along them at speeds as great as 50 cm. per second. The loss of blood, therefore, is very rapid and enough pressure to supply the brain cannot be maintained in the rest of the circulation, so that the victim becomes unconscious.

By the time the blood has reached the capillaries into which the smaller arteries branch, it is travelling much more slowly, at a rate nearer 0·05 cm. per second. These capillaries are too small to be seen with the unaided eye and in them the pulse is lost. They run through all parts of the body and are very numerous in the surface skin. If blood-capillaries are cut (as when we prick a finger or scratch the skin), the blood flows very slowly, and it very quickly *clots** (see Book Four, Chap. VI).

From the capillaries the blood passes slowly into the veins, which often run near the surface of the body (e.g. they may most easily be seen under the skin on the back of the hand). A cut vein bleeds without any jerking flow (i.e. there is no pulse in veins); the deoxygenated venous* blood is at first dark red and the bleeding may be stopped by pressure on the side of the wound *away* from the heart. Veins differ from arteries in that most of them contain valves, which prevent the backward flow of blood, while the pressure in them is never high. The movement of blood towards the heart is helped by the body-muscles near the veins, when these muscles contract during the normal movements of an animal. If we stand still for a long time the blood is not in this way squeezed* back to the heart quickly enough; it then tends to collect in the veins of

the legs and the shortage of blood in the head may cause us to faint and become unconscious.

THE LUNG CIRCULATION

A simplified diagram of the circulation of the blood is shown in Fig. 64. The two upper (anterior) chambers of the heart are known as the *auricles*;† the lower (posterior) pair are the *ventricles*,† and these, especially the left ventricle, are very thick-walled. The de-oxygenated dark-red blood, rich in carbon dioxide and coming from all parts of the body (except the lungs), flows into the right auricle, which contracts regularly and pumps blood into the right ventricle (see Fig. 65). When this is full it contracts in its turn and forces the blood through a large artery towards the lungs (the *pulmonary*† *artery*). Valves between auricle and ventricle and at the entrance to the pulmonary artery ensure that the blood does not pass back from ventricle to auricle, nor from the pulmonary artery to the heart, during relaxation of the ventricle at the end of its 'stroke'. In the lungs the arteries divide into smaller branches, and these divide again and again to form very narrow or *capillary* blood-vessels, which run through the thin walls surrounding the air-sacs in the lungs (see Fig. 61). As the blood passes into these tiny capillaries, it not only exposes a larger surface, but its rate of movement is very greatly slowed down (as when a river flows into a wide swamp)*. Thus in the lungs the blood travels along very slowly and there is time for gaseous exchange to take place. The blood, of course, never comes into actual contact with the air in the lungs, but is separated from it only by the thin walls of the capillaries and of the air-sacs. These walls are always wet, so that carbon dioxide and oxygen dissolve in the water in the thin walls and pass through them. There is always a considerable loss of water from the lungs, removed in the expired air, for the thin wet walls of the air-sacs lose water by evaporation into the spaces of the lungs. This evaporation is, however, diminished* if breathing has taken place through the nose (see p. 98).

The exchange of gases between blood and air in the lungs takes

place by *diffusion* (see Book Two, Chap. IV). The gases carbon dioxide and oxygen pass from places where they are in high concentration to places where they are in lower concentration. Hence, in the capillaries of the lungs, oxygen passes from the air-sacs into the blood and carbon dioxide passes from the blood into the air-sacs. The capillary blood-vessels, which form a fine network in the lungs, all join together again to form large veins that carry the *oxygenated* and 'carbon-dioxide-poor' blood (which is now bright red) to the left side of the heart (along the *pulmonary vein*).

Blood consists of a watery '*plasma*'† containing dissolved food substances and numerous small suspended *red blood-cells* containing the colouring matter *haemoglobin*.† This substance plays a most important part in the transport of oxygen. It is normally dark red, as we see it in the veins. When combined with oxygen (as in the arteries, or when the blood is exposed to air) it becomes bright red. Owing to the presence of haemoglobin, the blood can take up, in the form of a loose chemical compound, about forty times as much oxygen as would be absorbed by simple solution of oxygen in the watery plasma, i.e. without haemoglobin the heart would have to pump blood at about forty times the normal rate to keep the body-cells supplied with the same amount of oxygen. The loose compound *oxy-haemoglobin*† is formed in the capillaries of the lungs and easily breaks down again in the capillaries of the rest of the body, the oxygen being taken from it and used in respiration. The carbon dioxide given out by the body-cells is also taken up by the blood, partly in combination with haemoglobin, but mostly by other complex chemical reactions, and it is readily released again from the blood in the capillaries of the lungs.

THE BODY CIRCULATION

Bright-red oxygenated blood from the lungs enters the left auricle (see Fig. 65), whence it is pumped into the left ventricle through another non-return valve. This ventricle in turn contracts and the blood is forced through yet another valve into the largest artery, the *aorta*. This branches and distributes the blood to smaller

and smaller arteries, which carry the blood to capillary blood-vessels, thus supplying food and oxygen to all parts of the body (except the air-sacs of the lungs, which have their own separate circulation). From the capillary blood-vessels of the body-circulation, the blood is collected by veins that join together and finally bring this de-oxygenated blood (which has given up part of its oxygen and has taken up carbon dioxide and dissolved food) to the right side of the heart. This completes the body-circulation, and the right heart-pump sends this de-oxygenated blood to the lungs once more. The veins leading from the capillaries of the intestines do not pass the blood directly back to the heart; they join together into a large *portal*† vein that passes to the *liver* and there branches again into capillaries. The liver is a sort of chemical laboratory for the body; sugary food brought to it in the blood along the portal vein is dealt with in the liver, some of it being stored as a starch-like substance, *glycogen*,† while the rest passes on, by way of the heart, to the other parts of the body. The liver also deals with any proteins not required for body-building, breaking them down and liberating sugars (which are used in respiration), together with the waste product *urea*,† a substance that is later removed from the body by the *kidneys*. The living cells of the liver obtain their oxygen from blood brought directly to them in the *hepatic*† *artery* (see Fig. 66).

Scientific men have known something of the arrangement of the vascular system in mammals for nearly two thousand years, but it was not until the seventeenth century that a clear account of the circulation of the blood was given by Harvey. When you have seen an animal dissected and have noticed the great complexity of the vascular system, you will understand the difficulties that stood in the way of this work. The early scientists believed, for example, that the right and left sides of the heart communicate directly with each other, and they were very confused by the fact that the pulmonary artery to the lungs carries dark red blood, while the aorta and all other arteries to the body carry bright red blood. A combination of careful and accurate *observation and experiment*,

coupled with a better understanding of the chemistry of respiration, opened the way to our modern knowledge, which we can now summarize in diagrams like Figs. 64, 65, and 66.

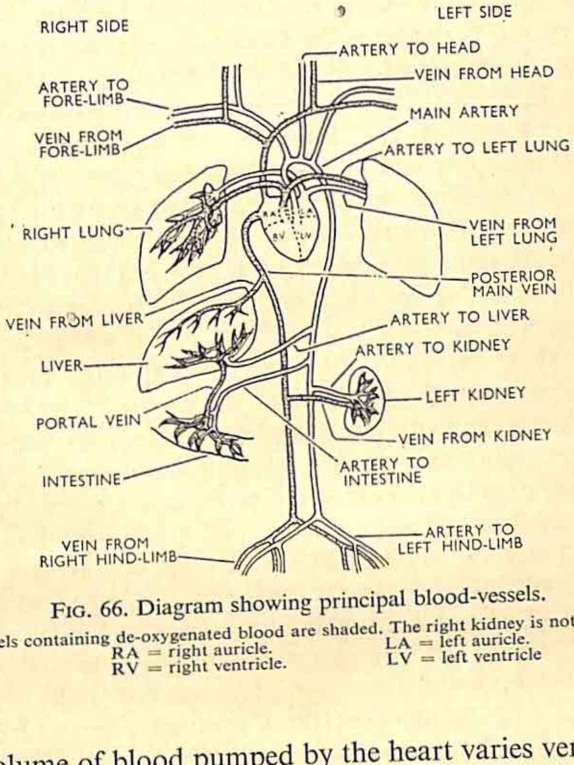


FIG. 66. Diagram showing principal blood-vessels.

Vessels containing de-oxygenated blood are shaded. The right kidney is not shown.
RA = right auricle. LA = left auricle.
RV = right ventricle. LV = left ventricle

ARTERIES

The volume of blood pumped by the heart varies very considerably according to the amount of oxygen used by the muscles. When the human body is at rest, the left ventricle pumps, each minute, about $2\frac{1}{2}$ pints of blood into the main artery, and a similar quantity is pumped to the lungs. During violent exercise, e.g. running up a long flight of stairs, this volume may be increased three or four times in order to supply the extra oxygen needed by the muscles. Under such conditions, therefore, the pressure on the walls of the large arteries becomes very great, and these arteries have strong,

but elastic, muscular walls. The sudden rush of blood when the ventricles contract is most violent in the arteries nearest the heart, and these main arteries have the thickest walls. The walls become thinner as the arteries branch and the blood flows more gently and smoothly, until by the time the blood reaches the capillaries there is no longer any pulse, and the walls of the capillaries are very thin, usually only one cell thick. Such exceedingly thin walls allow exchanges between the blood and the body-tissues,* and the *tissue-fluid*† acts as a 'middle-man' between the two. The diameter of a capillary is very little bigger than that of a single red blood-cell, and its length may be only one-fiftieth of an inch, yet in this short space between the end of an artery and the beginning of a vein the blood exchanges food and oxygen for carbon dioxide and other waste products.

In Man, the *main artery* (or *aorta*) is about one inch in diameter and its walls are about 3 mm. thick. It arises from the left ventricle, and soon after leaving the heart it gives off (i) left and right branches carrying blood to the head, and (ii) left and right branches carrying blood to the fore-limbs. The main artery then turns over to the left and continues down the body, close to the backbone, passing through the diaphragm, into the belly-cavity (or *abdomen*).

Immediately after passing through the diaphragm, the main artery gives off a branch artery to the *liver* and *stomach* and, a little farther on, it gives off branch arteries to the *intestine*. About the same region, the main artery gives off left and right branches to the *kidneys* and, farther on, other branch arteries that supply blood to the hind-limbs (see Fig. 66).

VEINS

The arteries carry blood away from the heart, and the capillaries join the arteries to the veins, which return de-oxygenated blood to the heart. The blood from the capillaries has a very low pressure and no 'pulse', hence there is no need for the veins to have thick, strong walls. Veins have only a thin layer of muscle round them, and the flow of blood back to the heart is assisted by the pressure

of the body-muscles and by pocket-like *valves* (rather like the valves in the large arteries where they leave the heart) (see Fig. 65). During exercise, as the muscles move, they press on the veins and so squeeze the blood along towards the heart, the valves preventing 'back-flow'. Breathing movements also help in returning blood from the main veins to the heart. The main veins enter the *right auricle*. The two *anterior main veins* (left and right) bring blood from the upper part of the body, while the *posterior main vein* brings blood from the lower part of the body. Each anterior main vein receives several branch veins: (i) two veins that carry blood from the head, and (ii) veins carrying blood from the *fore-limbs* and the *walls of the chest-cavity*. The posterior main vein lies close to the main artery in its course down the body and receives (*a*) a vein from the *liver*, (*b*) two veins from the *kidneys*, (*c*) veins from the *back*, and (*d*) veins from the *hind-limbs* (see Fig. 66). Another important vein, the *hepatic portal vein*, has already been mentioned on p. 108.

THE BLOOD

We have seen that the blood is concerned with *transport* in the animal body. *It carries* (*a*) *food from the intestines to the body-cells*, (*b*) *oxygen from the lungs to the body-cells*, (*c*) *waste products from all parts of the body to the lungs and kidneys*, (*d*) *heat produced by working muscles, and* (*e*) *hormones* (discussed in Book Four).

The average man has about 10 pints of blood in his body. Under resting conditions only part of this blood is actually circulating, the rest being held in reserve, mainly in the *liver* and *spleen*†. The blood makes up about one eleventh part of a man's body-weight.

When a drop of blood is spread out into a thin film and examined under the microscope, it is seen to consist of a clear, colourless liquid, *plasma*, in which float *blood-cells*. These blood-cells are of two distinct kinds—*red blood-cells* and *white blood-cells* (see Fig. 67).

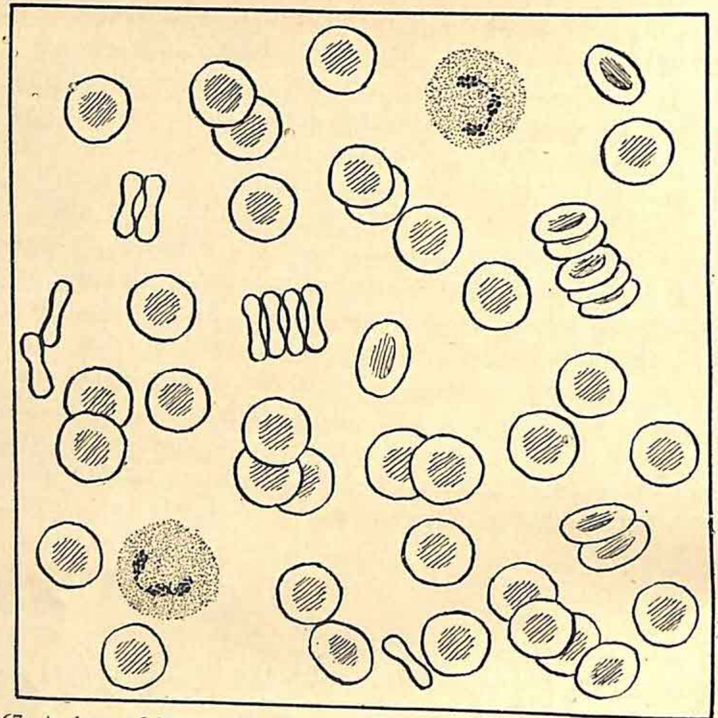


FIG. 67. A drop of human blood seen under the microscope showing many red blood-cells and two white blood-cells (highly magnified).

RED BLOOD-CELLS

The red blood-cells (or *red corpuscles*),† which are from 500 to 1,000 times more numerous than the white cells, are shaped something like a concave lens, i.e. they are circular in outline and thicker round the edge than in the middle. Under the microscope they appear yellow, but when seen massed together in large numbers, e.g. in a drop of blood, they appear red. This red colour is due to the presence of *haemoglobin*, a protein substance containing iron, which readily combines with oxygen.

These red blood-cells are formed mainly in the red *marrow*† of bones, and then they enter the blood-stream, where their active

life lasts for a few weeks only. After this they are broken down in the *liver* and in the *spleen*, some of the waste products being excreted in the *bile*. In this way millions of red blood-cells are destroyed and replaced every second.

WHITE BLOOD CELLS

The white blood-cells (or *white corpuscles*) are much fewer in number than the red cells. There are usually between 500 and 1,000 red cells to every single white cell. Some of the white blood-cells are formed in the red bone-marrow, others in the *lymph*† *glands*, and their active life lasts for a few days only. Unlike red blood-cells, the white corpuscles have no definite shape and can thus squeeze their way out through the thin walls of the capillary blood-vessels and reach almost any cell in the body.

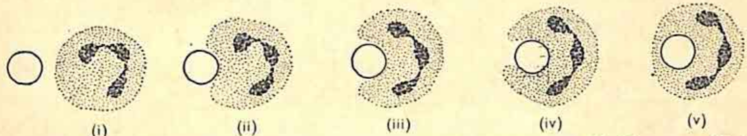


FIG. 68. A white blood-cell surrounding a micro-organism (highly magnified).

There are several kinds of these white blood-cells. One kind of white cell surrounds and digests bacteria that may enter the body, thus defending the body against bacterial infection.* One of these white cells may surround and digest as many as twenty invading bacteria (see Fig. 68). Some white blood-cells also set free substances that are poisonous to bacteria. In the normal healthy body, these white blood-cells are victorious over the bacteria that enter the body. If the skin is cut or broken, white blood-cells collect in large numbers to remove bacteria and damaged body-cells. The *pus*† that collects round some wounds consists mainly of dead white blood-cells, dead bacteria, and decomposed body-cells.

TISSUE-FLUID AND LYMPH

As the blood flows slowly through the capillaries, part of the watery blood-plasma (containing some white blood-cells) escapes

through their extremely thin walls and surrounds the neighbouring body-cells. This *tissue-fluid*, which you may regard as blood without its red cells, surrounds all the body-cells and fills the tiny spaces between the body-cells and the capillary blood-vessels, acting as a 'go-between' or 'middle-man' between the blood on the one hand and the body-cells on the other. The tissue-fluid takes oxygen and food materials from the blood and hands them on to the body-cells. At the same time, it takes up carbon dioxide and other waste products from the body-cells. This 'used' tissue-fluid is known as *lymph*.

Since tissue-fluid is always escaping from capillaries all over the body, the lymph that it forms must be collected up again and returned to the blood-stream once more. Some of it re-enters the capillaries and is carried on to the veins, but the remainder enters small *lymph-vessels* that later unite to form larger vessels which finally open into large veins near the heart, thus returning the lymph once more to the blood-stream. The amount of lymph passing through the lymph-vessels is only about 10 pints (4–5 litres) per *day*. The lymph-vessels have even thinner walls than veins and, since the lymph they contain is almost colourless, the *lymphatic system* is very hard to make out in an ordinary dissection. In Book Four you will learn that digested *fats* are absorbed from the intestine through the lymph-vessels.

EXCRETION

In its widest meaning, the term *excretion* means the removal of all waste matter from living things. In green plants, the waste matter consists of (*a*) carbon dioxide, produced during respiration, and (*b*) excess oxygen, produced during photo-synthesis. These are easily lost to the surrounding air, no part of the living plant being far from the surface or from an internal air space. With plants a great deal of water is lost (transpired), but as we do not usually regard this water as waste matter, transpiration is not regarded as a form of excretion. Moreover, the water is not actually pushed

out of the plant, but simply evaporates from exposed wet surfaces within the leaves.

Animals, with their more compact bodies, cannot get rid of the waste product, carbon dioxide, as easily as plants; in addition, they usually produce an excess of nitrogen-containing waste substances. There are, in all higher animals, special *excretory organs* that remove these waste materials from the body.

Of the food taken into the food-canal of a mammal, a certain proportion is indigestible and is never absorbed into the blood-stream. This unabsorbed, more or less solid, waste passes right through the food-canal and is finally passed out from the *anus* as *faeces*. Strictly speaking, this undigested matter has never been inside the living cells of the animal's body. The food-canal is open to the outside world at both ends—mouth and anus—and it is only after the digested part of the food has passed through the walls of the food-canal that it is considered to have entered the tiue interior of the body.

The digested, soluble, food is absorbed into the blood-stream and passes to the living cells. As a result of the complicated chemical processes that go on in these cells waste products are formed. The most important of these are (i) *carbon dioxide* (formed during oxidation of food-material), (ii) *nitrogen-containing compounds*, such as *urea* (formed when proteins are broken down), and (iii) *water*.

Most of the carbon dioxide and some of the water are given up by the blood as it passes through the lungs, and thus escape into the atmosphere each time the animal breathes out. The air we breathe out contains much more carbon dioxide than the air we breathe in (actually about a hundred times as much). The large amount of water vapour in the air we breathe out can be shown by breathing on to a sheet of polished glass: it becomes covered with tiny drops of condensed water.

Animals contain a much larger proportion of protein than plants, and they produce larger quantities of nitrogenous waste products, which are excreted by special organs. In mammals the

kidneys remove *urea*, dissolved in water, from the blood. The kidneys consist of numerous microscopic 'kidney-tubes' in close contact with capillaries carrying blood. Water, urea, and some salts pass from the blood into these 'kidney-tubes', which join together into *kidney-ducts*,* or *ureters*,† that lead into the *bladder*.† The solution—*urine*—drains through the ureters into the *bladder*, where it is stored up and passed out at intervals (see Fig. 69).

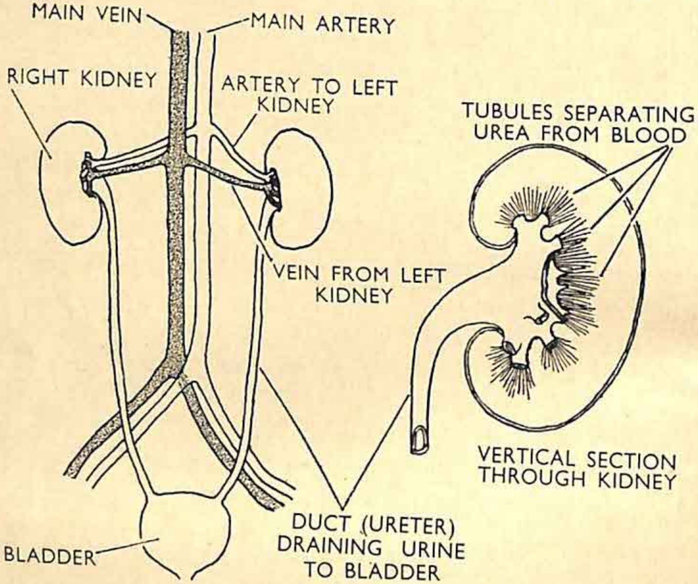


FIG. 69. The kidneys (diagrammatic).

The greater part of the waste products, therefore, are got rid of through the *lungs* and through the *kidneys*. In some mammals, however, large quantities of water (and some salts) are lost by the *skin* as *sweat* if the outside temperature is high, but this loss of water and salts that takes place during sweating is *not* to be regarded as *excretion* of waste products; like transpiration in plants, sometimes it may actually be harmful. However, apart from any question of excretion, the evaporation of sweat from the

skin is accompanied by cooling of the body, hence sweating is a process that is more important in connection with the regulation of body temperature than as a method of excreting water.

CELLS AND TISSUES

Every living thing is built up of very small units called cells. Cells were first described by Robert Hooke in the seventeenth century, when he noticed the 'honeycomb'* appearance of a thin slice of cork when viewed through the microscope. He gave the name 'cell' to each tiny box in the 'honeycomb'. This name was rather unfortunate, for it suggests a hollow, empty box; yet *living* cells are neither empty nor hollow. The cork that Hooke examined was dead, and the living contents of the cells had disappeared. What Hooke saw was merely the dead *cell-walls*. Nearly 200 years later, it was found that the living parts of plants and animals are made up of cells containing a semi-liquid *living* jelly, called *protoplasm*, and nowadays the term 'cell' is applied to the living contents (the protoplasm) rather than to the dead case (the cell-wall).

Plant cells are surrounded by a dead cell-wall composed of *cellulose* (a carbohydrate). Animal cells have no such dead cell-wall, hence it is more difficult to distinguish the outline of individual animal cells under the microscope. The greater part of each of these animal cells consists of colourless, jelly-like *protoplasm*, the outer layer of which is a little more solid than the remainder, thus forming an elastic, living membrane. In the middle of each cell is the rounded *nucleus* that controls all the activities of the cell. Such cells, of different patterns, shapes, and sizes, are the units from which an animal's body is built up.

Each individual living cell, however, is a living thing in itself and, under suitable conditions, it can be separated from the rest of the body and kept alive (by the method of 'tissue-culture'). *Each single cell carries out all the living processes*, e.g. it feeds, respires, and grows. Besides this, when a cell reaches a certain size, it may divide into two parts, each containing half the original nucleus,

i.e. *each living cell can reproduce itself*. We see, therefore, that a single cell—a particle of protoplasm controlled by a nucleus—is the simplest living thing,[1] containing in its tiny body everything necessary for life. The simplest animals and plants are microscopic in size and consist of only one single cell. In these, as well as in the biggest and most complex living things, all the essential functions of life take place *in the individual cells*.

TISSUES

The body of a higher animal or plant is built up of many different kinds of cells, each kind being adapted to carry out some particular function; in other words, the higher animals show *division of labour*.* For example, some cells are nerve-cells, some are muscle-cells, some are reproductive cells, and so on.

Each of these special kinds of cells performs one special function better than any other, and masses of such specialized cells are grouped together to form *tissues*. For example, masses of nerve-cells are known as *nerve-tissue*; large numbers of muscle-cells form *muscle-tissue*. Other kinds of specialized cells form *covering-tissue*, *binding-tissue*, and *strengthening-tissue*.

ORGANS

Complicated body-structures like the heart, stomach, liver, brain, eye, and ear are called *organs*, and every organ is formed of a number of different *tissues*. The eye, for example, contains covering tissue, binding-tissue, muscle-tissue, nerve-tissue, and blood-tissue, each tissue carrying out its own special work but all of them working together as parts of a single organ carrying out a *minor** function of the body.

SYSTEMS OF ORGANS

In the body of a higher animal, the various organs are grouped together into *systems*, each system having its own special work in carrying out a *major** function of the body. For example, all the

[1] Apart from a *virus*† (discussed in Book Four), which is non-cellular.

digestive organs—mouth, tongue, throat, gullet, stomach, intestine, salivary glands, liver, gall-bladder,† and pancreas—together form the *digestive system*. In studying the higher animal we have to consider the *skeletal system*, the *muscular system*, the *respiratory system*, the *digestive system*, the *blood system*, the *excretory system*, the *nervous system*, and the *reproductive system*. *The animal body, or the complete ORGANISM, therefore, is built up of SYSTEMS; these systems are built up of a number of ORGANS; the organs are made of several different TISSUES, which are collections of similar CELLS, the cell being the smallest living unit.*

THE SKELETON

Mammals are built around a framework of *bones*, called the *skeleton*. These bones not only stiffen the body and give the animal its definite and characteristic shape, but they also help in *movement*, for most of the *muscles* are attached to them. Parts of the skeleton, the *skull*† and the *backbone*, also protect the delicate *brain* and *spinal cord*.†

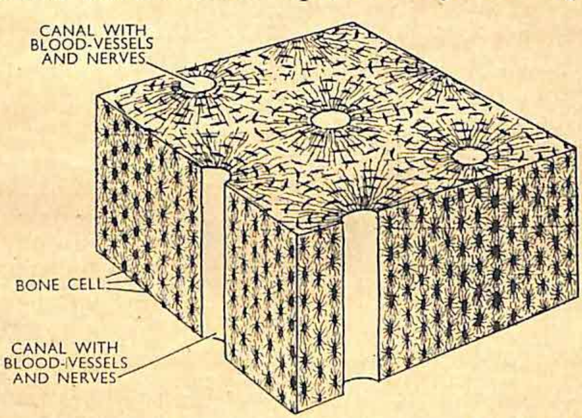


FIG. 70. Bone structure. The diagram shows a small block of bone, highly magnified.

The bones of a living animal are themselves alive, being supplied with blood-vessels and nerves (see Fig. 70). They grow, like the

other, softer parts of the body. In a very young animal they are soft and flexible,* but later they become brittle* and hard. If a bone is broken, the two parts are capable of 'growing together again', i.e. new bone tissue is formed across the breakage.

Bones are very rich in calcium and phosphorus compounds, but, being alive, they also contain *organic* matter. If a bone is heated red-hot, all the organic matter burns away and only the hard *inorganic* (or mineral) matter is left. If a bone is treated with dilute hydrochloric acid, the mineral matter (calcium carbonate and calcium phosphate) dissolves and only the soft organic matter is left. The inorganic matter makes bone very dense, and most of the larger bones are hollow, giving equal strength with less weight.

This bony framework is built on the same essential ground-plan in all the *Vertebrates*† (animals with *backbones*), e.g. fish, frog, bird and mammal, consisting of a *main axis** (*skull*, *backbone*, *ribs*, *breastbone*) and two pairs of attachments (limbs) which may be either legs or arms or fins* or wings. These are attached to two *limb girdles*† that form part of the skeleton (see Fig. 71). An *internal skeleton* does not give such complete protection to the soft parts of the body as does the external skeleton of an insect, but it does not hinder growth and is better adapted to free body-movements.

THE SKULL

The skull, or head-skeleton, is built up of a number of plate-like curved bones joined together at their edges. It gives protection to the soft, delicate brain and to the sense-organs—eyes, ears, and nose. It also carries the *jaws*. The upper jaw is firmly attached to the skull, while the lower jaw is attached by *tendons*† and muscles, being freely hinged* to move up and down. The lower jaw can also move slightly from side to side, and (in gnawing* mammals—the *rodents*†) from back to front.

THE BACKBONE OR SPINAL COLUMN

The skull is hinged to the backbone, which is built up of a large number of separate bones (*vertebrae*†) joined together, end to end,

by *ligaments*,† so as to form a strong column that can twist and bend slightly (see Fig. 71). The separate bones are prevented from rubbing or striking against each other by disc-shaped cushions of

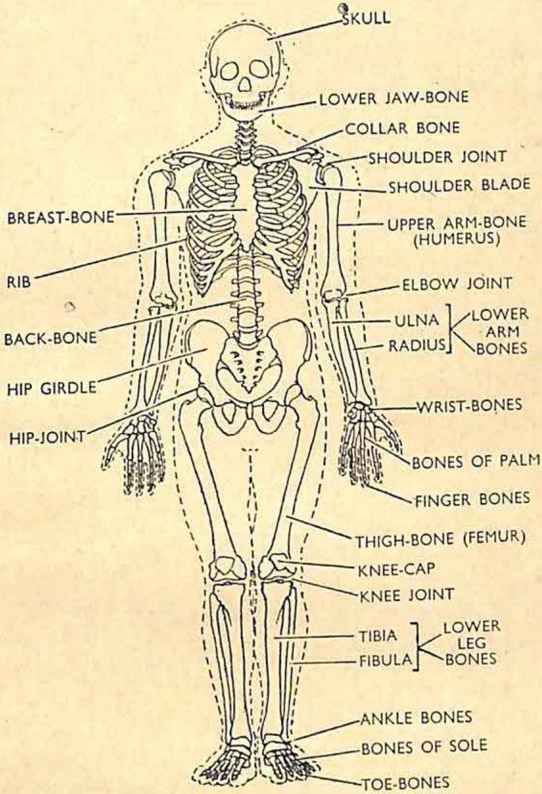


Fig. 71. The human skeleton.

gristle†, or *cartilage*†, a stiff, but elastic, substance. The cushions of gristle act as 'shock-absorbers', protecting the brain and spinal cord from shock at every step we take as we walk.

This backbone forms the main axis of the skeleton. Each separate vertebra has a hole through it, so that when all the bones

are joined, end to end, these holes form a continous tube running from the skull down through the length of the backbone. The *spinal cord*, which arises from the hinder end of the brain, runs through this tube inside the backbone and is thus well protected from harm (see Fig. 72).

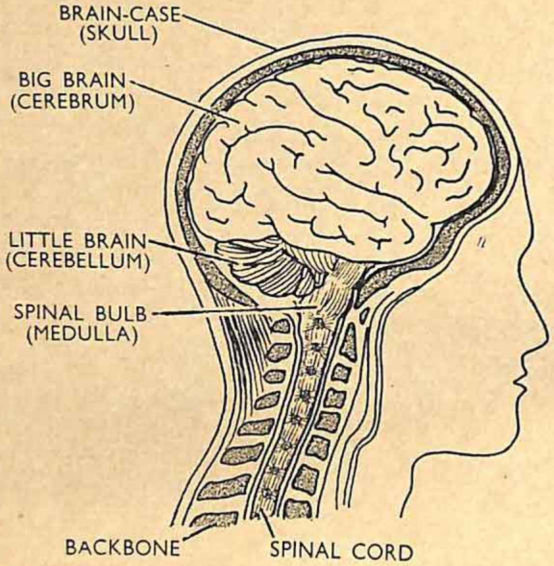


FIG. 72. Diagram showing human brain and part of spinal cord.

THE RIBS

In mammals, the ribs form part of a bony cage enclosing the *thorax*, or chest-cavity. In Man, there are twelve pairs of ribs and they are all attached to the backbone by tough, fibrous ligaments (see Fig. 71). The first seven pairs of ribs (counting from the anterior end) are also attached to the breastbone in front. The front ends of the next three pairs of ribs are not attached directly to the breastbone but to a piece of gristle that joins them to the breastbone, while the last two pairs are attached to the backbone only.

The *fore-limbs* are connected to the trunk through the *shoulder-girdle*,† which consists of a pair of *shoulder-blades*† and a pair of *collar-bones*.† The shoulder-blades are large, triangular bones and they are attached to the backbone and ribs by strong muscles and tendons (but there is no *bony* connection). The collar-bones are small, curved bones connecting the outer end of the shoulder-blade with the breastbone, thus supporting the fore-limbs (see Fig. 71).

The upper part of the fore-limb (the upper arm in Man) consists of a single long bone (*humerus*†), jointed to the shoulder blade on the 'ball-and-socket' principle. The lower part (the lower arm or fore-arm in Man) consists of two bones (*radius*† and *ulna*†), hinged to the upper-arm bone at the elbow. Then there are several wrist-bones, and beyond these the bones of the hand and of the fingers (see Fig. 71).

The bones of the *hind-limbs* are connected to the *hip-girdle*,† and this, in turn, is firmly attached to the backbone. Hence the hip-girdle is much more rigid than the shoulder-girdle, which has no direct bony connection with the backbone. This results in much greater freedom of movement in the fore-limbs than in the hind-limbs. In Man, the whole weight of the trunk is carried by the very strong hip-girdle, to which very powerful muscles are attached.

The hind-limb is built on the same general plan as the fore-limb. The strong *thigh*†*-bone* (or *femur*,† the largest bone in the body) has a rounded head that fits into a deep socket in the hip-girdle (see Fig. 71). The lower part of the hind-limb consists of two leg-bones (*tibia*† and *fibula*†) joined together and hinged to the thigh-bone at the knee-joint. Beyond the leg-bones are the ankle-bones, corresponding to those of the wrist in the fore-limb, and joining the leg-bones to the foot-bones. In Man, the arch* of the foot gives springiness to the whole skeleton and helps to protect the brain and spinal cord from shocks.

Every muscle of movement is attached to at least two jointed bones, and nearly all these muscles are arranged in pairs—one muscle bringing the jointed bones closer together when it contracts

and the other muscle pulling the bones back to their original position once more. Feel the biceps† muscle tendon in the hollow of your elbow, also the prominent* tendon that joins your calf-muscle† to your heel-bone. (*N.B. Tendons* usually join bone to muscle; *ligaments* usually join bone to bone.)

MUSCLES AND THEIR ACTION

Muscle plays a very important part in an animal, for all animal movements are brought about by the shortening and thickening of muscle fibres. Muscle is a form of living substance that has the power of *contraction*; under certain conditions it can alter its shape, increasing in thickness while decreasing in length. It is both *extensible* and *elastic*. In a mammal the muscles occupy a big proportion of the whole body, e.g. the 'fleshy' parts of the arms, legs, back, and body walls are all muscle; in fact, muscle is the most abundant tissue in the body. The red flesh of higher animals ('lean meat') is largely muscle.

When muscles shorten and thicken, they *do work*, and they obtain the energy for this from respiration, which goes on in the living muscle cells. These are well supplied with blood-vessels, bringing food and oxygen and taking away the waste products formed when food is oxidized. Only a part of the energy set free by muscle-respiration is used in *work*; much of it appears as *heat*. In fact, the chemical changes taking place in muscle-contraction supply the greater part of the heat that, in mammals and birds, keeps the animal warm.

We distinguish between two chief kinds of muscles. The *voluntary* muscles* are those whose movements are short and rapid and under the *conscious control* of the animal. They cover the skeleton and are connected by tough, cord-like *tendons* to bones. Most voluntary muscles are arranged in pairs, each pulling in opposite directions (though not at the same time). Fig. 73 shows how the muscles are attached to the bones of the arm and shoulder in Man. The arm is caused to bend at the elbow by shortening and thicken-

ing the *biceps muscle*, accompanied by relaxing and lengthening the *triceps*† *muscle*.

Involuntary muscles undergo slow, sustained* movements that, in the main, are not under conscious control. These are the muscles that alter the 'bore' or *calibre** of the digestive, excretory, and circulatory tubes, and hence serve what may be called the

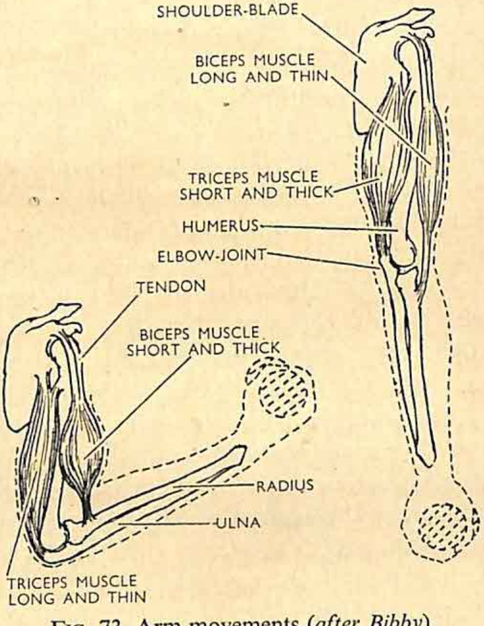


FIG. 73. Arm movements (*after Bibby*).

'domestic arrangements' of the body—e.g. digestion, circulation and excretion.

The part played by the two kinds of muscle may be illustrated as follows: *Voluntary muscles* move the limbs that guide the food to the mouth (e.g. in Man), and move the lower jaw up and down during eating. Once the food has been swallowed, movements of the *involuntary muscles* force it along the food-canal. It is possible to spit out food that is still in the mouth, but once the food has

passed into the gullet it is usually impossible to return it to the mouth by voluntary effort.

THE SKIN

The skin, with its underlying layer of fat, separates the body from the outside world, protecting it from cold, wet, hurt, and bacterial infection. Man, especially in cold climates, adds to this natural body-covering by wearing artificial clothing. The skin also plays an important part in regulating body-temperature by sweating.

The *outermost layer* of the skin consists of *dead cells* that have become horny* plates. These dead cells are usually rubbed off from time to time, but in some parts of the body, where there is pressure or friction, they accumulate and form a thick, horny layer, e.g. in Man, on the underside of the foot, the palm of the hand, and the front of the fingers and thumbs. There are few nerves or blood-vessels in this dead outer layer, hence there is little pain or bleeding when the *outer* layer is cut. As the outer layer of dead cells wears away, the cells are replaced from the layer of living cells that lies below this outer non-living skin (see Fig. 74).

Each *hair* arises from a narrow tube or *hair-pit* in the skin. *Oil-glands*,† opening near the root of each hair, produce an oil that makes the hair waterproof and also softens the skin. Brushing spreads this oil along the full length of the hair. Small muscles are attached to the pit enclosing the root of the hair and, when these muscles contract, the hair 'stands on end'.

In the deeper layers of the skin (the *dermis*†, lying below the *epidermis*†) are *sweat-glands*, each consisting of a spiral tube, coiled into a knot at its inner end and opening at the surface of the skin through a *sweat-pore*. The sweat-pores are not evenly distributed over the surface of the body, e.g. there are about 3,000 per square inch on the palm of the hand, but only about 500 per square inch on the back of the trunk. The sweat-glands are surrounded by a network of capillary blood-vessels from which they absorb

water containing very small quantities of dissolved salts and urea. It is chiefly by evaporation of sweat that the body-temperature is regulated. The deeper layers of the skin contain a network of blood-vessels, and by varying the calibre of these capillaries another method of regulating body-temperature is possible (discussed in Book Four, Chap. VI).

The *sense-organs of touch*—warmth, cold, pain, and touch—are just below the outer skin (or *epidermis*). These sense-organs

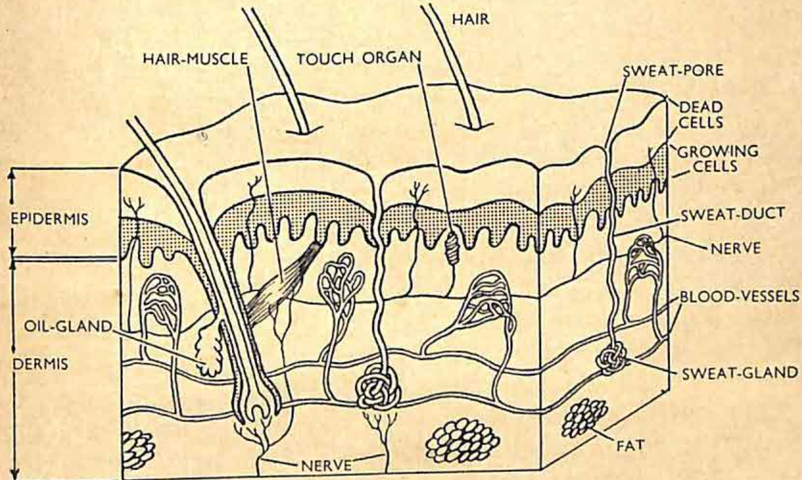


FIG. 74. Skin structure. The diagram shows a small block of human skin, highly magnified (*after Bibby*).

(*receptors*†) are the endings of nerves that carry sensations to the *central nervous system*—the brain and spinal cord.

Just below the innermost layer of skin (or *dermis*) lie deposits of *fat*—a bad conductor of heat—which reduces heat loss from the body. This layer of fat is particularly important to mammals that live in water. Whales, for example, whose body-temperature is much the same as our own, have a thick, uniform layer of fat (blubber†) that prevents loss of heat through their skin to the surrounding cold water.

One of the most important differences between living and non-living things is that living things are *active* and can adapt their behaviour to changes in their surroundings. In the animal world, this *response to an external stimulus* in higher animals has to be more rapid than in plants, and this response is brought about by their complicated *nervous system* and their muscles.

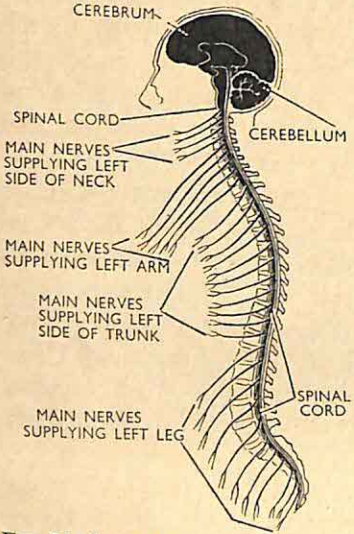


FIG. 75. Central nervous system and main nerves (diagrammatic).

A mammal moves by means of muscles attached to its jointed bones. These muscles are very numerous and very complicated in their action. For example, in our own body, when we walk, from the time we press on the ground with our right foot until we press on the ground with our left foot, half a second later, we use about 300 muscles! In a higher animal, provided with hundreds of different muscles, all able to pull in various directions, it is clearly necessary to direct and control them so that they all work in the right way and at the right time. This is the work of the *nervous system*, consisting of the *nerves*, the *spinal cord*, and the *brain* (see Fig. 75). The brain and the spinal cord form the central, unifying part of this nervous system. The work of the nerves is to carry impulses from the sense-organs or *receptors* to this *central nervous system* and then from the central nervous system to the various muscles and glands (or *effectors*)† of the body.

THE NERVES

*A nerve carries impulses.** This is its only function. The nerves in an animal's body correspond to the wires that run from house to

house in a telephone system. The nerves carry impulses from the receptors *inwards* to the brain and spinal cord, and they also carry impulses from this central nervous system *outwards* to the effectors. The nerves that carry impulses *inwards* from the sense-organs are called *sensory* nerve-fibres* and they give rise to the *sensations* of sight, hearing, taste, smell, touch, temperature, pain, movement, and balance. The nerves that carry impulses *outwards* to the muscles and make them move are called *motor* nerve-fibres*. The nerves that one sees as white threads in a dissection are bundles of nerve-fibres, and they may contain both sensory and motor nerve-fibres lying side by side. In such cases, we speak of *mixed nerves*, because some of the fibres give rise to sensations and others control muscle movements.

In the same way as the nerves correspond to the street-wires in a telephone system, the central nervous system (brain and spinal cord) corresponds to the central telephone exchange. This central nervous system sorts out messages received from the receptors through the sensory nerves and sends out suitable responses along the motor nerves to the muscles and other effectors. These responses that take place through the central nervous system are of two kinds: (*a*) *voluntary actions* and (*b*) *reflex† actions* (or involuntary actions).

Voluntary actions are controlled by the will. Reflex actions are unconscious responses to stimuli.

REFLEX ACTION

With practice and training, many voluntary actions become reflex actions. In other words, we develop a *habit*. For example, when learning to shoot with a rifle; we have to make a special effort of the will to keep the left eye closed while we take aim with the right eye, but after a time it is closed *automatically*, and *unconsciously*, as soon as the rifle is brought into the aiming position. Similarly, when one learns to swim, every new movement of the limbs requires a special effort of the will, but once one has *learnt* the strokes, the muscles carry out the necessary movements

automatically, without any conscious effort of the will. In the same way, when learning to ride a bicycle, it is only by voluntary action that one turns the front wheel so as to avoid falling off. When this action becomes automatic, we have 'learnt to ride'.

The simplest response of an animal to an external stimulus is a reflex. As an example of a reflex, consider what happens when you sit down by accident on a sharp, pointed object. You jump up immediately, without having to think about it. This is a *reflex action*, and like most other reflexes, it is a *protective response*, since the body would have been hurt if it had been left sitting on the sharp object. Although the complete reflex occupied only a fraction of a second, *three parts of the nervous system are concerned*: (*a*) *a sensory nerve*, (*b*) *the spinal cord*, and (*c*) *a motor-nerve*. First of all, sensitive nerve-endings in the touch-organs of the skin are affected by the pain-stimulus and send a message along *sensory* nerve fibres to the spinal cord. Then a message is sent out by the nerve-cells of the spinal cord along the *motor* nerve-fibres to the voluntary muscles concerned, which contract and move the body away from the source of the pain-stimulus. The inward passage of the sensation and outward passage of the stimulus to the muscles together form a *reflex arc*,* and this is the path of a *simple involuntary reflex* (see Fig. 76).

VOLUNTARY ACTION

In 'higher' animals, such simple *spinal reflexes* are usually only the first stage in the animal's reaction to a stimulus. The message from the touch-organs in the skin finally reaches the *brain* and gives rise to sensations of touch and pain. In some cases, the brain sends a message to stop the reflex action. For example, if you pick up a hot object in the dark, your simple protective reflex response to the pain-stimulus will be to drop it and your brain does not interfere. But suppose you are doing an experiment in the laboratory and have already weighed a crucible very carefully. Then, after heating it, you forget that the crucible is still hot and pick it up with your fingers. Your automatic reflex is to drop it; but unless the

crucible is very hot, you will make an effort of the will and put the crucible down gently so as to avoid having to start the experiment over again. That is, in a fraction of a second, by *reasoning*, you decide that it is better to suffer temporary discomfort rather than give yourself half an hour's extra work. In this case, the simple reflex has been controlled and modified* by the *brain*. The nerve-impulse from the finger-tips has not been dealt with merely in the

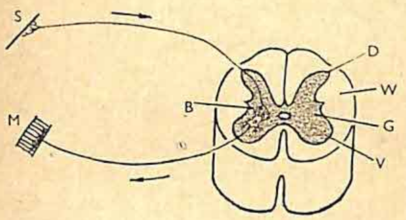


FIG. 76. Diagrammatic section across spinal cord showing path of simple involuntary reflex.

W = white matter (nerve-fibres). G = grey matter (nerve-cells). S = sensitive nerve-ending in skin. M = muscle at outer end of motor nerve. D = dorsal horn of grey matter. V = ventral horn of grey matter. B = inter-communicating branch between nerve-cells in spinal cord.

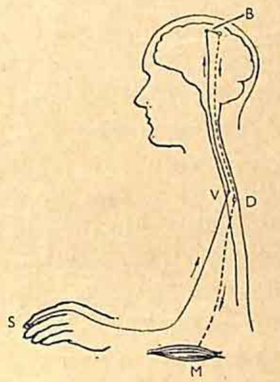


FIG. 77. Simplified diagram showing path of modified reflex, controlled by brain.

B = inter-communicating branch between nerve-cells in brain.

spinal cord but has travelled up to the brain (see Fig. 77). *Simple reflex actions have their centre in the spinal cord or in the hind-brain. Voluntary actions have their centre in the fore-brain.*

Like reflex actions, voluntary actions involve receiving a stimulus through a receptor and the transmission of the impulse inwards to the central nervous system and outwards again to the muscles, but *in a voluntary action the path of the nervous impulse is much longer than in the case of a simple reflex action*, and there is often some delay between receiving the external stimulus and the voluntary action that results from it. In practice, simple reflexes are uncommon, and the nervous impulse that travels to the spinal cord or

to the hind-brain is usually transmitted to the fore-brain as well, and this part of the brain controls and modifies the simple reflex action.

The nerves from the eyes, ears, mouth, nose, face, neck, and some of the internal organs, run directly to the brain, independently of the spinal cord.

THE CENTRAL NERVOUS SYSTEM

In a mammal, the *central nervous system* consists of the *spinal cord* and the *brain*. The brain is the enlarged and specialized anterior end of the spinal cord, so we shall describe the spinal cord first, before going on to the brain, which is more complicated.

The Spinal Cord. The spinal cord, which runs down through the middle of the backbone, is made up of *nerve-fibres* (white) and *nerve-cells* (grey). The white nerve-fibres lie round the outside of the spinal cord, and the grey nerve-cells are massed together in the middle. In cross-section, the 'grey matter' is shaped rather like an 'H'. The *sensory nerve-fibres*, carrying impulses inwards, lead into the two dorsal horns of the 'H'-shaped grey matter, while the *motor nerve-fibres*, carrying impulses outwards, arise from the two ventral horns of the 'H'. Running down the middle of the spinal cord is the *central canal*, containing liquid. The spinal cord is divided into right and left halves by two deep grooves in its dorsal and ventral surfaces (see Fig. 76).

The Brain. The spinal cord becomes larger and more complex at its anterior end. As the spinal cord enters the head, it expands to form the *spinal bulb*.† This part of the brain controls the involuntary movements of the body, e.g. breathing, heart-beat, and the movements of the food-canal during digestion. Above the spinal bulb is the '*little brain*' (or *cerebellum*†)—a swelling whose surface appears to be folded. The little brain sees that all the body-movements are in step with each other. It is responsible for *balancing* the body-movements, e.g. if the '*big brain*' orders a movement of one limb, the little brain automatically sends out impulses that cause movements of other parts of the body so that it does not overbalance.

Anterior to the little brain is the *big brain* (or the *cerebral hemispheres*†), which forms the largest part of the brain in mammals. (see Fig. 72). The big brain is the centre of all conscious, voluntary actions and sensations, e.g. will, memory, reasoning, and feeling.

In the brain, most of the nerve-*cells* (the grey matter) lie on the outside of the nerve-*fibres* (the white matter), the converse of the arrangement in the spinal cord. Since capacity for conscious voluntary actions, e.g. will, memory, reasoning, sensation, and feeling, depends on the number of nerve-*cells* present in the brain, it is clearly an advantage to have the grey matter spread out in a thin layer (0·1 in. thick in Man) over the *outside* of the brain, where it can continue to grow and extend without any pressure from surrounding parts. In the highest animals, the area of grey matter is still further increased by a folding of the surface of the big brain.

In proportion to his size, Man has the largest and most folded big brain of any animal. Man is the most *intelligent** animal. He can *reason* or 'think things out', he can ask questions, and he can decide between right and wrong. In the lower vertebrates, which are much less intelligent and which give no evidence of having the power of reasoning, the grey matter of the big brain is much less well developed.

CHAPTER III

OTHER LIVING THINGS

THE SIMPLEST LIVING THINGS. EVOLUTION

The Earth was once very hot, and under such conditions there could be no living things on its surface. As the Earth cooled and its surface layers contracted, water collected in hollows on its surface, and it is believed that living things first arose in these waters. These early forms of life must have been exceedingly simple, and it is reasonable to believe that they were like the simplest living things we know today. In these simple forms of life, the plant and animal worlds overlap, and it is difficult to decide which are *plants* and which are *animals*. The simplest living things are very small in size and very simple in structure, consisting of *one single cell.*

AMOEBA—A VERY SIMPLE ANIMAL

Amoeba† is a very simple animal consisting of a single cell. There are various kinds of Amoeba; some live in fresh water, some in sea-water, some in the soil, and some in the bodies of higher animals as *parasites* (e.g. one causes amoebic dysentery† in Man).

The fresh-water Amoeba is a tiny particle of protoplasm, just visible to the unaided eye, about 0·01 in. in length. Under the microscope, Amoeba is seen to consist of a single cell of no definite shape (see Fig. 78). The nucleus is a small, rounded body inside the protoplasm. Although Amoeba is so small in size and so simple in structure—just a single particle of protoplasm—it carries out the same fundamental life-processes as the higher animals: (*a*) *movement*, (*b*) *nutrition*† (or feeding), (*c*) *respiration* (or getting energy by oxidizing food), (*d*) *excretion* (or getting rid of waste products), (*e*) '*feeling*' (or response to changes in its surroundings), (*f*) *growth*, and (*g*) *reproduction*.

Movement. Amoeba changes its shape by making its protoplasm flow out in the direction in which it wants to travel, thus slowly rolling along, rather like a 'caterpillar'* tractor or tank.

Nutrition. When Amoeba gets near a food-particle (usually a microscopic one-celled water-plant) it simply flows round the food, encloses it in its protoplasm, and then digests it (see Fig. 78). The digested food is then absorbed and used for growth, or oxidized to liberate energy.

Respiration. The water in which Amoeba lives contains dissolved oxygen that is absorbed through its surface layer. The digested food is oxidized and the carbon dioxide formed is got rid of by diffusion through the surface layer into the surrounding water.

Excretion. When a living Amoeba is examined under the microscope, there can be seen a space, filled with a clear liquid, that

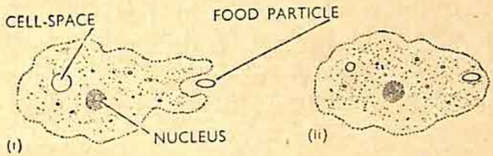


FIG. 78. An Amoeba feeding (magnified).

gradually grows larger as we watch it and then suddenly disappears as it squeezes out its contents into the surrounding water. In this way, excess water containing dissolved waste products is got rid of.

Response to Surroundings. Amoeba is *sensitive* to changes in its surroundings. It moves slowly at low temperatures and more rapidly as the temperature rises. It flows round food particles and encloses them in its body, but it avoids solid particles that are useless as food, and merely flows round one side of such objects. It moves away from bright light. These '*responses to external stimuli*' show that Amoeba is *irritable** or sensitive to changes in its environment.

Growth and Reproduction. As Amoeba feeds it grows, but only until it reaches a certain size. When this size is reached, the animal

divides into two. The nucleus first divides into two halves and each half becomes surrounded by protoplasm.

The two halves then separate from each other, and one parent Amoeba becomes two new animals that proceed to grow until they are big enough to divide and reproduce themselves in turn.

SPIROGYRA—A VERY SIMPLE PLANT

Spirogyra† is a very simple green plant found floating in fresh water. It consists of long green threads. Under the microscope, each thread of Spirogyra is seen to be made up of a number of cylindrical cells, joined end to end (see Fig. 79). Although the cells are joined

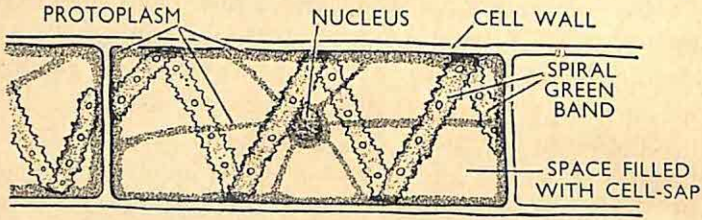


FIG. 79. Spirogyra cell (magnified and diagrammatic).

together at their ends, each single cell is a self-contained individual plant, living independently of its neighbours on either side. Each cell is only a fraction of a millimetre long. It has a cell-wall, of *cellulose*, enclosing the colourless protoplasm that lines the cell-wall and extends in threads to the centre of the cell, where the nucleus is suspended. A specialized part of the protoplasmic lining forms a spiral green band—the *chloroplast*.

A single Spirogyra cell carries out the same fundamental life processes as Amoeba, except that it shows little movement. Its *nutrition*, however, shows a fundamental difference from that of Amoeba, since Spirogyra, like all green plants, manufactures its food from very simple raw materials—carbon dioxide, water, and mineral salts—in the presence of sunlight. These nutrients are absorbed through the cell-wall. In the light, some of the oxygen set free during photo-synthesis is used for *respiration*, and the carbon

dioxide that is produced is used during photo-synthesis. In the dark, however, dissolved oxygen is absorbed from the surrounding water and used for oxidizing food and liberating energy, while the carbon dioxide that is produced diffuses out through the cell-wall. When a Spirogyra cell has grown to its full size it divides into two new cells, which remain attached end to end.

IMPORTANT DIFFERENCES BETWEEN AMOEBA AND SPIROGYRA

Amoeba differs from Spirogyra in several important respects. In the first place, having no cell-wall, Amoeba can take in solid food, digest it by means of special digestive juices, and get rid of solid waste matter. Spirogyra, on the other hand, feeds on inorganic nutrients absorbed in solution through the cell-wall and built up into manufactured food with the aid of leaf-green and sunlight.

Amoeba, therefore, is a typical *animal*, while Spirogyra is a typical *plant*, although both are among the simplest and most primitive living things. A great many simple organisms like Amoeba and Spirogyra are found living in fresh- and sea-water.

EVOLUTION: 'THE LADDER OF LIFE'

It is clear that there are very great differences between the appearance and method of living of Spirogyra and a plant like the Sunflower, or between Amoeba and Man. We usually describe this difference by saying that the Sunflower is one of the '*higher*' and Spirogyra one of the '*lower*' plants. Similarly, Man is regarded as the '*highest*' animal and Amoeba as one of the '*lowest*'.

The 'lowest' living things are those with fewest parts and the simplest structure. 'Higher' living things are more complicated and have many different parts, each doing special work. Between the highest and the lowest living things we find every degree of increasing complexity. This has given rise to the idea of an *evolution*† from the lower to the higher forms of life. In other words, we believe that each kind of living thing has been developed (or has *evolved**), by a very slow process of change, from pre-existing simpler living things.

As Charles Darwin (1809–1882) first clearly showed, there is a great deal of evidence in favour of this *theory of evolution*. In fact, biologists are now certain that evolution has taken place and is still going on. The strongest evidence for evolution comes from *fossils*. Embedded in the sedimentary rocks are found the compressed remains of plant and animal *species*† (kinds) that no longer live on the Earth. Some of these fossils resemble present-day plants, while others are 'missing links' that fill some of the gaps between the 'lower' and the 'higher' organisms we know today. The older the rocks, the simpler are the fossils found in them. Fossils of mammals and flowering plants, for example, are not found in rocks that are known to be older than about 150 million years.[1]

Another kind of evidence for evolution is *geographical*. The peculiar distribution* of many animals and plants (e.g. the restriction of most pouched* mammals, such as kangaroos, to Australia) can be simply explained if we assume that these creatures evolved *after* their continent or island had become separated from the rest of the world.

There is no doubt that some groups of animals and plants have evolved more quickly than others, so that today we find, still living side by side, the advanced 'higher' organisms and the simple 'lower' organisms, which latter probably do not differ much from their early ancestors.*

THE SMALLEST LIVING THINGS: BACTERIA

Bacteria are the smallest known living things with a cellular structure.[2] These colourless, one-celled micro-organisms (or *microbes*†) exist wherever organic matter is found: in soil, in water, and in the air. Since most of them have no leaf-green (*chlorophyll*) they cannot use light energy in synthesizing their food, as do green plants, but they must get their food in other ways. In this, bacteria

[1] The age of the Earth (from the time that its solid crust was formed) is about 2,000 million years, and fossils have been found in rocks at least 700 million years old.

[2] A *virus* is an organism smaller than any bacterium, but it is non-cellular.

resemble* animals, but since they are enclosed in a cell-wall they can only absorb dissolved food, thus resembling plants. But their cell-wall is not composed of cellulose, like most plant cell-walls, and the modern view is that bacteria can be regarded as plants, closely related to the fungi.

Single bacteria measure from 0·0001 in. to 0·00001 in. and can only be seen under very powerful microscopes. Different kinds of bacteria have different shapes, being either spherical, rod-shaped, or spiral, and they often group themselves together in masses or in straight chains (see Fig. 80). Many bacteria can swim in water. In all of them the cell is bounded by a membrane (but this is not made of cellulose) and the organism cannot take in solid food. Although most of them do not contain chlorophyll, some can make their own organic food from simple inorganic materials: they do not, however, use light energy for this purpose. Others get ready-made food from dead plants and animals. Still others are *parasites*; they are able to enter other living organisms and take food from them. In doing so they often cause disease in, or the death of, their hosts.

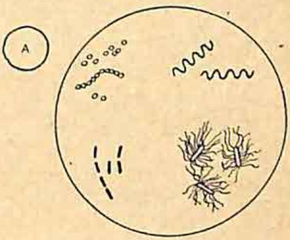


FIG. 80. Some types of bacteria (magnified about 1,000 times). (The red blood-cell A is drawn to the same scale.)

Bacteria reproduce themselves by splitting into two, and the two new bacteria grow so quickly that they are ready to divide again in about thirty minutes. Hence, in ten hours, under favourable conditions, a single bacterium can produce over a million bacteria. When conditions are unfavourable, e.g. when the liquid in which they are living dries up, some bacteria produce *spores*, and in this form they may be scattered in all directions, floating in the air, ready to germinate when they reach a suitable situation. These tough-walled spores are the most resistant form of living matter. Some bacterial spores have been known to germinate even after being kept in liquid air (at $-190°$ C.) for six months, but practically all spores are killed by boiling for twenty minutes.

EVERYDAY IMPORTANCE OF BACTERIA

Bacteria have a very important influence indeed on other organisms. Soil bacteria are partly responsible for the nitrogen and carbon cycles; in particular the nitrogen-fixing bacteria of the legume root-nodules* improve soil fertility. The breakdown of organic materials in soil largely benefits the higher plants and animals. The bacteria that live in the intestines of grazing animals digest the cellulose in their food and in this way provide the animals (and themselves) with sugar.

Man has learned to use some bacteria almost as 'domesticated plants'. Thus the 'curing' of tobacco, the ripening of cheese, and the making of vinegar* are all reactions carried out by bacteria. To Man, however, the bacteria are a mixed blessing. With the moulds and other fungi they are largely responsible for spoiling foods like milk, butter, eggs, and meat. Moreover, many of the important diseases of Man (e.g. tuberculosis,† typhoid fever†) have now been shown to be due to the activities of parasitic bacteria.

THE EVOLUTION OF PLANTS

SEAWEEDS—MARINE ALGAE

One can find simple green plants, like Spirogyra, in almost any lake or pool. They are classed together as the *Algae*.† The more advanced types of this large and varied group are much more common at the sea-coast, growing in the sea-water and mostly attached to rocks (see Fig. 81). Some of them are green, forming long threads or flat plates. Most of them, however, are *brown* or *red*, for their green chlorophyll is hidden by other, darker, colouring matter. All the algae carry out photo-synthesis and take up mineral salts and water from the sea-water (which is a complete natural 'culture solution') directly through their outer surfaces. As we might expect, they are not found (as are sea-animals) at a depth greater than that to which sunlight reaches. Their main interest to biologists is their very complicated method of reproduction (see

Book Four, Chap. X). The *brown* seaweeds are often very large and their structure resembles that of the flowering plants, although they have no true roots, no vascular system of wood-vessels and bast-vessels, and they do not produce flowers. Biologists believe that many of them resemble those primitive many-celled marine* plants that first colonized the dry land.

The algae are not restricted entirely to the sea-coast. Free-floating, one-celled forms exist in vast numbers on the surface of all the oceans and, together with microscopic animals, they form the floating marine *plankton*,† which is the main food of fishes.

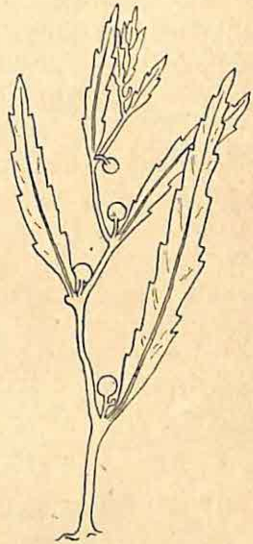


FIG. 81. A seaweed plant.

MOULDS, MILDEWS, AND MUSHROOMS—THE FUNGI

The *fungi* are non-green plants that resemble the bacteria in many ways. One well-known fungus is *yeast*.† Yeast is one-celled, but it is much larger than any bacterium. Also, its cell has a well-marked *nucleus* (absent in bacteria) and the cell-wall is made of a kind of cellulose. Yeast can only grow when supplied with *organic* food. It is important to Man because it converts sugar into alcohol (see Book Four, Chap. III).

Most fungi are not one-celled but *filamentous*,† like some algae, being built up from large numbers of cells joined end to end. Most of them are *saprophytes*,† i.e. they feed on *dead* plant or animal tissues, and they live in rich soil, decaying organic matter, on bread, jam,* and leather. In the *moulds*, the fungus plant is a loose network of fine white threads (or *filaments*)† growing in and on the food supply. Moulds reproduce themselves very efficiently, largely by means of *spores*, which they form in vast numbers. These spores are therefore to be found floating in the air on dust particles all

over the Earth. You can get a mould to grow in any warm place if you cover a piece of damp bread with an inverted beaker (so as to keep it damp). In a day or two, the bread will be covered with a thick growth of the mould called *Mucor*,† and this will soon produce a crop of black spore-cases. You may also find another common mould, *Penicillium*,† which produces green spores at the ends of microscopic brush-like filaments (but the green colour is not due to chlorophyll) (see Fig. 82). One variety of Penicillium produces the wonderful substance *Penicillin*,† which, while quite harmless to Man, prevents the growth of many disease-producing bacteria.

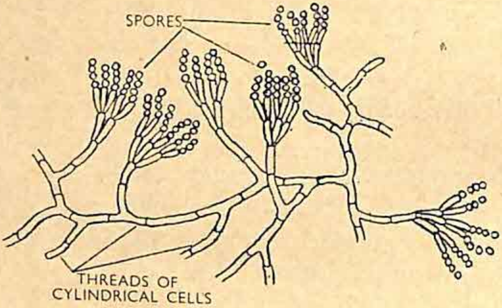


FIG. 82. A mould plant.—Penicillium (magnified).

Other fungi, rather like the moulds, are the *mildews*.† These are *parasites* on the stems and leaves of living plants. One such parasite is unusual in causing a skin-disease of Man—*ringworm*.† Fungi that live in wood and reduce its strength are also common, and some of them (e.g. 'dry-rot'†) cause serious damage to structural timber* in buildings. The so-called 'higher fungi' are very common in the soils of pastures and forests. Their underground *feeding-filaments* are not readily seen, but in wet weather they produce large *fruiting bodies* above ground—*toadstools*,† *puffballs*,† and *mushrooms*† (see Fig. 83). Most of these fungi that live in the soil play an important part in helping to break down the insoluble proteins and carbohydrates (e.g. cellulose) in plant

remains, and they help the bacteria in forming humus. Fungi, like bacteria, can produce *enzymes* that pass outside their own bodies and cause the break-down of insoluble organic materials. The soluble products are then absorbed, in part, by the fungus cells and are used in their growth.

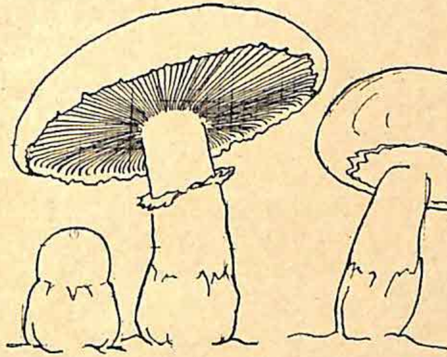


FIG. 83. Mushrooms: reproductive organs forming spores.

MOSSES AND FERNS

Most of the algae are water-plants, although some of the simpler types live in soil, on damp tree-trunks, or on damp rocks. But in almost any natural community* of plants one finds, besides flowering plants, other green plants that are intermediate in structure between the flowering plants and the algae. Some of the most important of these are the simple land-plants, *mosses* and *ferns*. A few of these can exist under dry conditions, but most of them grow best in damp (and usually shady) places.

The mosses (see Fig. 84) have very thin stems, seldom more than a few inches long, leaves that are usually only one cell thick, and no true roots. They absorb water and dissolved mineral salts from the soil through thread-like chains of cells (root-filaments) produced from the lower part of the stem. The cells in the moss stem show the beginnings of a 'division of labour', for the outer cells are thick-walled while the central cells are long and thin-walled (the

latter probably conduct substances along the stem), but there is no wood and bast as in 'higher' plants. In Book Four we shall learn how mosses reproduce *sexually*,* and also *asexually** (or vegetatively) by means of numerous air-borne *spores* produced in stalked spore-cases. Mosses can grow on rocks and in very shallow soils, where they help to prepare these for the growth of 'higher' plants.

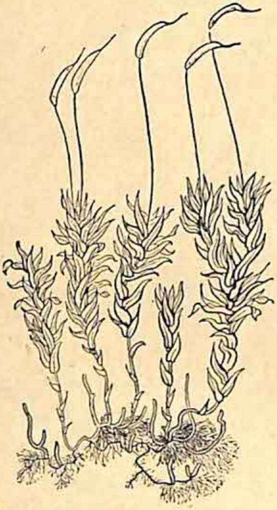


FIG. 84. A moss plant, with spore-cases.

FIG. 85. A fern plant.

Ferns are much more like flowering plants (see Fig. 85). They produce true leaves (often much divided) with stomates and veins, stems with true conducting-tissue (wood and bast), and true roots. In their method of reproduction, however, they are more like the mosses. Numerous *spores* are formed on the underside of the leaves and they produce no flowers. Related to the ferns are the less common *club-mosses*.† Fossil records (e.g. in coal-bearing rocks) show that large ferns and club-mosses were once the dominant

plants on the Earth's surface, but they now form only a small part of the Earth's vegetation.

HIGHER PLANTS

Still larger and more complex than the ferns are the *Conifers*† and the *Cycads*.† In these plants, *cones*† rather than flowers are produced, and a careful study of their life-history shows that they form a link between the ferns and club-mosses and the true flowering plants that are now the dominant plants of the world. Except for a few Conifers and Cycads, practically every plant used by Man for food, clothing, and timber is a flowering plant.

In Book Two we learnt that the flowering plants may be divided into two large groups. The *Monocotyledons* usually have narrow leaves with parallel or converging* veins, and their seedlings have only one seed-leaf, e.g. palms, grasses, and lilies. The more numerous *Dicotyledons* have broad, net-veined leaves and two seed-leaves in their seedlings. Many are non-woody *herbs*,* but some become woody and are able to increase their diameter by 'secondary growth' and thus develop into large trees.

EVOLUTION IN THE ANIMAL WORLD

The simplest animals, many of which live in fresh- and salt-water, and in the soil, resemble *Amoeba*. They are one-celled, small masses of protoplasm in which there is little specialization of parts. Some of them can swim rapidly in water owing to the movement of whip-like threads of protoplasm. They feed on micro-organisms like bacteria and on particles of dead organic matter. Some of them cause disease (see Book IIIA).

Some near relations of Amoeba build themselves shells of calcium carbonate, which they get from the calcium salts dissolved in sea-water. This chalky external skeleton protects their soft, jelly-like bodies. Enormous numbers of these tiny chalk-forming animals float in the oceans of the world, and, as they die, their mineral skeletons sink to the bottom, forming a deposit called *ooze*,† which covers about 30 per cent. of the ocean floor.

Under the great pressure of the water above it, this ooze becomes compressed into solid *chalk*, and when there are changes in the shape of the Earth's crust, some of this chalk is raised above sea-level. Whole ranges of mountains, e.g. large parts of the Alps, were originally formed in this way, and the formation of chalk still goes on at the bottom of the deeper seas to the present day. (Chalk, limestone, and marble, therefore, are called *organic rocks*.)

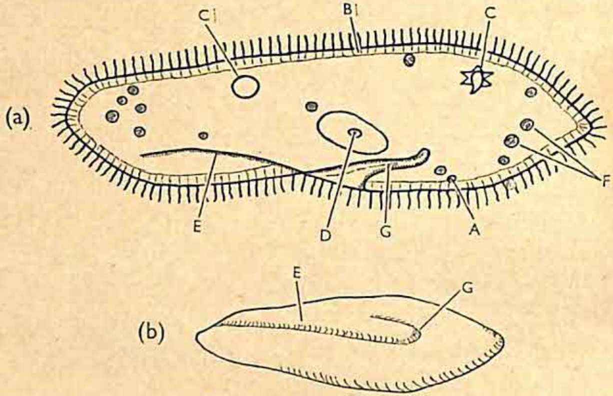


FIG. 86. Paramecium.

(*a*) Highly magnified. A = temporary anus; B = stiff outer layer of protoplasm bearing cilia; C = contracting cell spaces; D = nucleus; E = groove leading to G = gullet; F = food particles.
(*b*) Less highly magnified view showing: E = groove leading to G = gullet.

THE SLIPPER ANIMAL—PARAMECIUM

Another one-celled animal that shows the beginnings of specialized parts is *Paramecium*† (sometimes called *the 'slipper* animal'* because it is shaped like a shoe or slipper) (see Fig. 86). This tiny animal can usually be found in pools of fresh water containing decaying vegetable matter. It is about 0·01 in. long and can just be seen swimming about in the water. This movement is brought about by the movement of short, fine, protoplasmic threads (called *cilia*†) that grow out from the surface. As these cilia beat the water, bending and straightening alternately, the animal swims along. Unlike Amoeba, Paramecium is enclosed in a stiff outer layer, so that it does not change its shape as Amoeba does. The

most interesting thing about Paramecium, however, is that it shows the beginnings of a *food-canal*. On one side of the animal is a groove that serves as a 'mouth', leading to the 'gullet'. Special cilia sweep water, carrying food-particles, into this gullet and so into contact with the protoplasm, which closes round the food. The food particle, surrounded by a drop of water, moves slowly round the inside of the cell, always following the same definite path, and after the digested food has been absorbed, the undigested residue is got rid of, always at the same point in the surface. When conditions are favourable, Paramecium, like Amoeba, reproduces itself by division.

SIMPLE TWO-LAYERED, MANY-CELLED ANIMALS

The next stage in evolutionary progress upwards to the 'higher' animal is represented today by a number of many-celled single animals, whose bodies are only *two-layered*. They have mouths and hollow *digestive cavities* and considerable specialization of *tissues*. Most of them are found in fresh- or salt-water and for the greater part of their lives they are stationary, or free-floating.

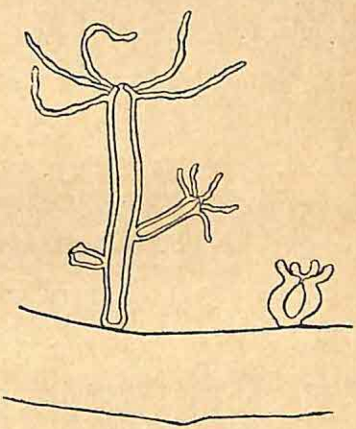


FIG. 87. Two Hydra animals.

One extended and the other contracted. The former animal has two 'buds'.

One of the simplest of these is the fresh-water *Hydra*,† which is commonly found attached to weeds in ponds. It is easily kept in an aquarium.* This animal is about 1 cm. long when expanded, but it contracts quickly when touched, forming a little ball. Its body is a hollow tube built up of *two layers* of cells, attached to a support at one end, which is closed (see Fig. 87). Round the other, open, end there are a few hollow threads, which wave about in the water and sweep

food particles into its 'mouth'. The cells in the outer layer of Hydra protect the animal and capture food, while those in the inner layer are concerned with digestion. Stinging cells are produced on the hollow threads surrounding the 'mouth', and when a small water-animal touches a stinging cell it is paralysed.* The hollow threads then close round the victim and draw it into the 'mouth'. Some of the cells lining the digestive cavity take in the smaller food particles (just as Amoeba does) and digest them. Other cells liberate enzymes into the cavity and these digest the larger food particles. There is no anus and waste products are excreted through the 'mouth'. Under favourable conditions, small 'buds' develop on the outside of the Hydra, and these grow up into new animals and then separate from the parent animal.

It is clear that Hydra is a considerable advance on the one-celled animals, since different work is carried out by different cells. For example, it has nerve-cells to 'tell' the animal when food has been caught, muscle-cells to close it into a ball when touched, stinging cells for capturing food, digestive cells lining the digestive cavity, and reproductive cells. In other words, there is some '*division of labour*' among the different kinds of cells, some of which carry out one function better than others. In Hydra, therefore, we see the beginnings of *tissues*, but there are no *organs*.

ANIMALS WITH A BODY-CAVITY BUT NO INTERNAL SKELETON

In still more advanced animals, the body has three (or more) layers, and a *body-cavity* develops between the outer layers and the inner *digestive tube*. This digestive tube is suspended in the liquid that fills the body-cavity. Such animals usually have a blood-system and a definite *head* (with sense-organs), distinct from the trunk. Simple animals of this general kind have no internal skeleton and are known as *Invertebrates*.† Some of them are symmetrical* about a centre (*radial symmetry*†), at least when adult, e.g. starfish† and sea-urchins,† but most of them have become *bilaterally symmetrical*,† i.e. they have developed distinct right and left sides. Such animals usually move about in search of their food.

We have seen that the most primitive animals, like the most primitive plants, live in water, and it seems likely that some simple animals became able to breathe dry air and could thus spend part of their life out of water. It is also probable that some plants had already left the sea for the dry land, so that food was available for animals that could live out of water. It is believed that the first animals to leave the sea for dry land were the *worms*, although many worms still live in the sea to this day. The 'lower worms' include round-worms† (thread-worms† and hook-worms†) and tape-worms,† some of them living in sea-water, some in fresh water, some in damp earth and others as parasites inside plants and animals. The bodies of the 'lower worms' (excepting tape-worms) are all in one piece, i.e. *they are unjointed*. The 'higher worms', or '*segmented*† *worms*', have *jointed bodies*, built up of a large number of rings or *segments*,* e.g. earth-worms. Worms are the simplest animals to have acquired* the habit of moving with one end always in front, so that from this stage of evolution onwards, animals have anterior and posterior ends, dorsal and ventral surfaces, and distinct right and left sides, i.e. they show *bilateral symmetry*.

EARTH-WORMS

Earth-worms are found in damp soil in nearly all parts of the world, but they need a fair amount of water and can only live for a short time in dry air.

The 'Indian earth-worm' (*Pheretima*),† common in many tropical countries, is reddish-brown in colour and has a long, narrow, cylindrical body, pointed at the anterior end and rounded at the posterior end (see Fig. 88). Its body is divided into a large number of rings or segments and is covered with a smooth, transparent skin. The skin is kept wet and slippery by a slightly alkaline liquid that escapes through pores in the worm's skin. This liquid is poisonous to the smaller enemies of the worm, e.g. soil bacteria, and it also serves to stick together the particles of soil forming the walls of its tunnel. Most important of all, since the worm breathes

through its skin, the liquid keeps the skin damp, so that exchange of gases can take place by diffusion.

The outer surface is not perfectly smooth, but there is a ring of tiny bristles* round the middle of each segment. In moving, a worm takes hold of the soil with the bristles of its hinder end and draws in the bristles near its head end. By means of muscles in its body-wall, the worm lengthens its anterior half and pushes its head end forwards. The worm then holds on to the soil with the bristles of its anterior end, draws in the bristles near its posterior end, and then contracts its body so as to draw forward the hinder end. In this way, the rings of a worm's body form longitudinal waves as it moves along.

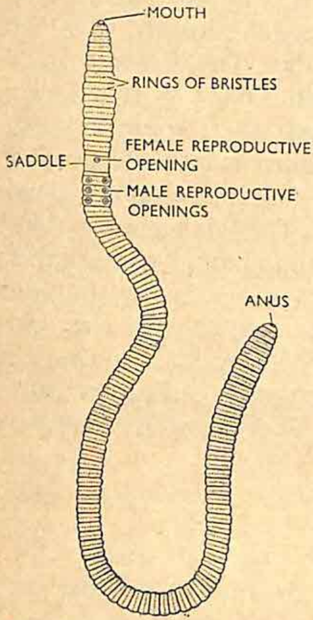


FIG. 88. Ventral view of Indian earth-worm (*after Bahl*).

The reddish-brown colour of the earth-worm is due to the presence of blood-vessels beneath the transparent skin. The main blood-vessel can be seen running along the whole length of the dorsal surface, below the transparent skin.

At the head end can be seen the *mouth*, and at the tail end there is the *anus*, these being the ends of the digestive tube or food-canal. At about one-eighth of the distance from the head to the tail (in segments 14, 15, and 16) the worm's body is surrounded by a smooth circular band, the 'saddle',* which is concerned with reproduction (see Figs. 88 and 89).

Earth-worms eat their way through the soil, sucking in and swallowing soil that contains particles of animal and vegetable matter. The food then passes along the *gullet*, where it is ground up very finely by the tough, muscular walls of the *gizzard*.† The food

then passes along through the *intestine*, where digestion and absorption take place (see Fig. 89).

The undigested soil passes out through the anus in small round 'worm-casts' and is left on the surface of the soil. When earthworms are plentiful, the amount of soil brought to the surface in

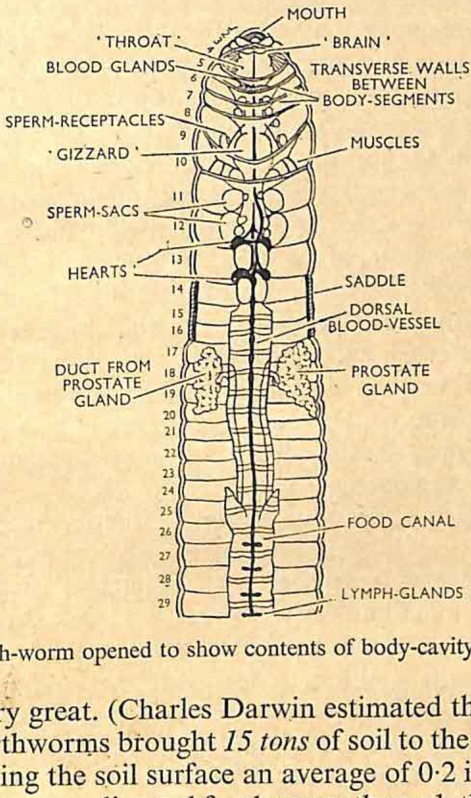


FIG. 89. Earth-worm opened to show contents of body-cavity (*after Bahl*).

this way is very great. (Charles Darwin estimated that in one acre of ground, earthworms brought *15 tons* of soil to the surface in one year, thus raising the soil surface an average of 0·2 in.).

In the earth-worm, digested food passes through the walls of the intestine, and is then transported to all parts of the body. The earth-worm does this by means of *blood* flowing through a '*closed system*' of *blood-vessels*. Food material is absorbed by small blood-vessels lying in the wall of the intestine, and is carried by the

bloodstream to all parts of the body through a system of tubes (see Fig. 89). Some of the blood-vessels contract and expand regularly, thus acting as 'hearts' and maintaining the circulation of the blood round the body. Besides carrying food, the blood also carries oxygen absorbed through the worm's skin, this oxygen being carried by *haemoglobin*, which is *dissolved in the blood* (and not confined in special red blood-cells as in the 'highest' animals). Carbon dioxide is also carried in solution by the blood from all parts of the body and is got rid of through the skin.

Hydra has a few cells that are sensitive to external stimuli, but in the earth-worm we find the first definite *nervous system*. A *ventral nerve-cord* runs along the whole length of the worm's body. This nerve-cord forms a small knot of nerve-cells in every segment and forms two larger knots of nerve-cells in the head region. This small mass of nerve-cells in the head is the primitive 'brain' of the worm. Although worms have no *organs* of sight and hearing, the skin contains sense-cells. Earthworms are very sensitive to touch and vibration, and they can also distinguish light from darkness. As the result of this primitive nervous system and its keen sense of touch, a worm represents the stage in evolution at which animals begin to show signs of *intelligence*.

We shall discuss reproduction and excretion in earth-worms in Book Four.

The earth-worm marks a very important step in evolution because it has a definite *body-cavity*, i.e. a space between the body-wall and the food-canal. In Hydra, the body-wall consists only of *two layers* of cells, and it encloses a *digestive* cavity, but there is no *body-cavity*. In the earth-worm there is a digestive *tube*, or food-canal, extending from mouth to anus. The digestive systems of all the higher animals have evolved from this primitive type. By having one tube (the food-canal) inside a second tube (the body-wall) the animal separates its undigested food (which may contain undesirable substances such as harmful bacteria) from its body-cavity. The body-cavity is the true interior of the body, and in higher animals it contains the main organs of the body.

A FURTHER STAGE IN THE EVOLUTION OF ANIMALS

The earth-worm shows a great advance over Hydra in having definite *organs*, each with its own specialized work to do but united in one body by a *system* of *nerves* and by the *circulation of the blood*. The next advance in structure is seen in the great group of animals with *jointed limbs* (the *arthropods*†), and these number about a quarter of a million different kinds, including *insects*, *crabs*,† *lobsters*,† *spiders*,† *ticks*,† *mites*,† *scorpions*,† *millipedes*, and *centipedes*.†

As in earth-worms, the body is built up of rings or segments, and some of these bear jointed 'limbs', including some that serve as 'jaws'. The skin is covered with a non-living *external skeleton* that is cast off* from time to time as the animal grows. We shall study two common insects as examples of this type.

INSECTS

GENERAL CHARACTERISTICS OF INSECTS

Among the 'higher', backboned (or *vertebrate*) animals, only the birds and the bats possess the power of flight. Among the backboneless (or *invertebrate*) animals only the *insects* can fly.

The body of any insect is divided into three distinct regions: (i) *head*, (ii) *fore-body* (or thorax), and (iii) *hind-body* (or abdomen).[1]

The *head* always bears a pair of *feelers*† (or *antennae*)† and three pairs of *mouth parts*.

The *fore-body* always consists of *three segments*, each segment bearing a pair of *jointed walking legs*, i.e. *three pairs of legs in all*. (The easiest way of distinguishing insects from other animals with jointed limbs is to count the number of legs. Thus spiders, which have four pairs of legs, are not insects.) The second and third segments of the fore-body (counting from the head end) usually

[1] N.B. The terms 'thorax' and 'abdomen' do not have the same meaning when applied to insects as they do when applied to higher, vertebrate animals (e.g. mammals). In this Course, therefore, we shall use the terms 'fore-body' and 'hind-body' when describing insects.

bear two pairs of *wings*, although a few primitive types of insects are wingless.

The *hind-body* consists of about ten segments, but these never bear legs or wings.

Another characteristic of insects is that the life-history and development is usually complicated, so that in the higher insects, e.g. butterflies† and moths, there is what is called *complete metamorphosis*,† i.e. the egg hatches* out into an active *larva* that later turns into a resting *pupa*,† until finally the perfect winged insect (or *imago*)† develops and completes the life-history.

The *insects* form a very successful group of animals, nearly as successful as Man himself, existing in enormous numbers and varieties. At least a quarter of a million different species of insects have been described by scientists. From Man's point of view, however, many insects are a nuisance because they are *parasites* on plants and animals. Some of them sting, some suck blood, some spread disease, and others attack crop plants; in fact it has been estimated that in the British Commonwealth alone, insects destroy enough food to supply the needs of 45 million people. Some insects, however, are helpful to plants and to Man, e.g. many of them are concerned in pollinating flowers.

We shall study two common examples of this large and important class of animals: (i) a *cockroach*,† one of the more primitive types (and showing *incomplete metamorphosis*†), and (ii) a *mosquito*, one of the 'higher' types (and showing *complete metamorphosis*).

THE COCKROACH

The cockroach is an insect with a history of millions of years, for fossils show that cockroaches were common in the forests from which our coal-deposits were formed. It is a very familiar insect in warm countries, hiding away in dark places during the day and becoming active at night, when it eats almost any organic matter, thus becoming a nuisance in houses.

The adult cockroach is dark-brown in colour, and its whole body

is covered with a thick, horny, *external skeleton*. The body is somewhat flattened above and below, and the three typical body regions—head, fore-body, and hind-body—are easily distinguished (see Figs. 90 and 92).

The head of the cockroach is short and wide, with the narrow end pointing downwards, and the mouth is at the tip of the narrow end. On either side of the head is a large, black, kidney-shaped, *compound eye*, made up of thousands of tiny lenses (see Fig. 91). Just below each eye arises a long, thin, many-jointed *feeler* (or *antenna*), a delicate sense-organ of smell and touch, which can be moved in all directions. The antennae of insects are used to *feel the way*, to *inspect food*, and to *communicate impressions* to one another.

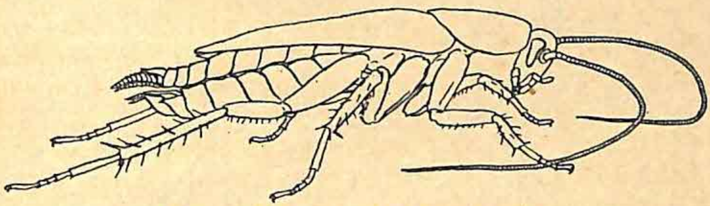


FIG. 90. Side view of male cockroach.

Around the mouth are three pairs of mouth parts for capturing and tearing up food (see Fig. 91).

The *fore-body*, which bears the organs of movement (legs and wings), consists of *three segments*. The first segment is the largest and bears a shield-shaped horny plate that extends outwards on all sides, hiding the neck and part of the head in front. The second segment bears a pair of dark-brown horny *wing-covers*, protecting the thinner pair of *flight-wings* borne on the third segment. The wings of insects are not *limbs* (like the wings of bats or birds) but merely *outgrowths** from a dorsal horny plate. The second and third segments of the fore-body are only seen when the wings are extended. All three segments of the fore-body bear a pair of five-jointed, clawed,* *walking legs*, arising from the ventral side (see Figs. 90 and 92 (*a*) and (*b*)).

The *hind-body* consists of ten segments, fitting into one another like the joints of a telescope.* (The last few segments overlap each other and are hard to distinguish.) The *anus* is underneath the last segment. This last segment also bears a pair of jointed rods. The *male* cockroach, in addition, bears a second smaller pair of unjointed rods on this segment. These are absent in the *female*, which

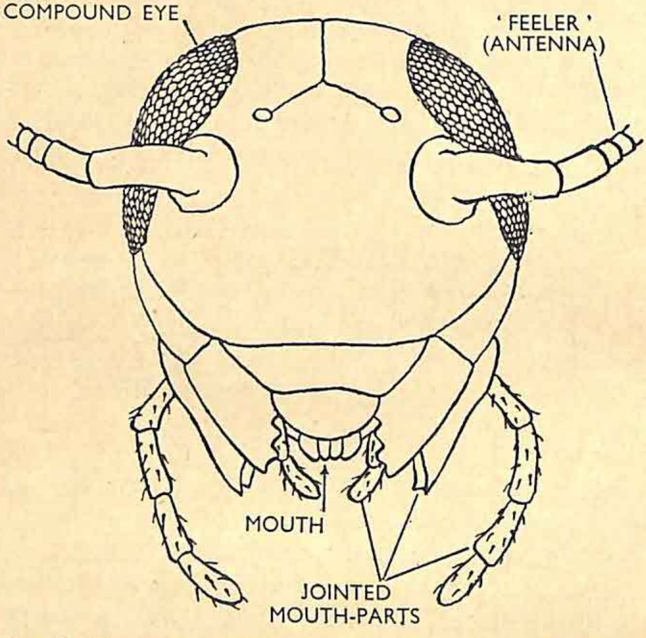


FIG. 91. Head of cockroach, seen from the front (much enlarged).

has a boat-shaped structure on the underside of the hind-body (see Fig. 92 (*c*)).

The cockroach has ten pairs of *breathing pores*, arranged on either side of its body—two pairs on the fore-body and eight pairs on the hind-body. These breathing pores lead to branching *air-tubes* that carry air to all parts of the body, supplying oxygen and removing carbon dioxide (see Fig. 92 (*a*)).

The female cockroach lays sixteen eggs at a time, packed in a dark-brown horny *egg-case*, about 10 mm. by 5 mm., formed in the boat-shaped structure on the under side of the female hind-body (see Fig. 92 (*d*)). When the egg-case is full, it is closed up and

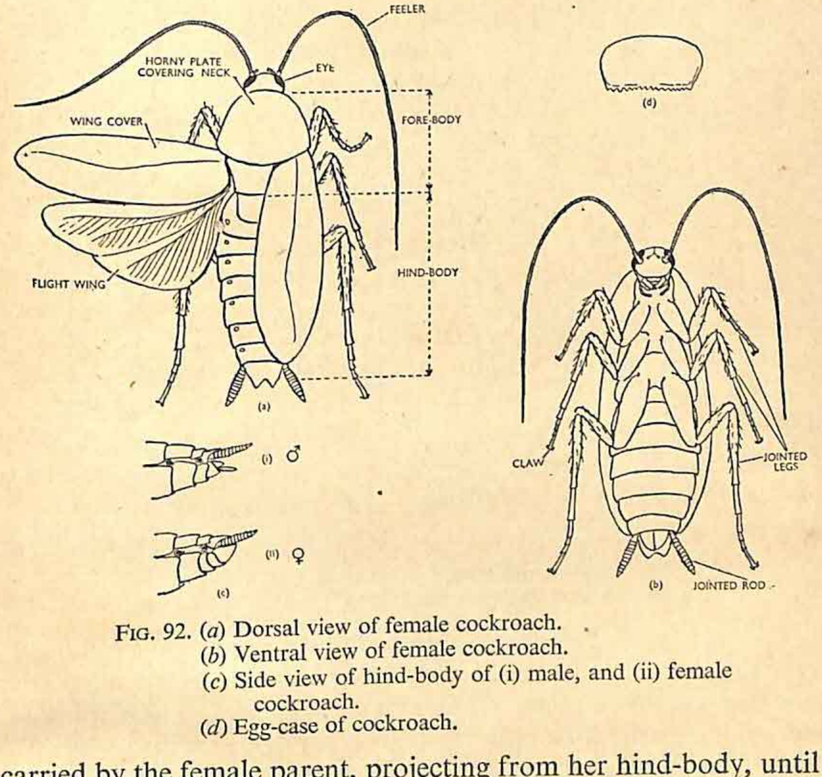


FIG. 92. (*a*) Dorsal view of female cockroach.
(*b*) Ventral view of female cockroach.
(*c*) Side view of hind-body of (i) male, and (ii) female cockroach.
(*d*) Egg-case of cockroach.

carried by the female parent, projecting from her hind-body, until she finds a suitable place to leave it. When the young cockroaches hatch out, they are similar to their parents in shape, but they are wingless and colourless. The young cockroaches grow rapidly and soon become too big for their horny skin (or external skeleton), which splits and is cast off. This process of *skin-casting* is repeated

several times as young cockroaches grow up, the horny skin being cast at intervals, and growth takes place before the new skin hardens. After the skin has been changed several times, small wings begin to appear, but it is not until after the final skin-casting that the wings reach their full size.

THE DIGESTIVE SYSTEM

The cockroach softens its foods with *saliva* from the *salivary glands* as it tears off and crushes food with its mouth parts. The

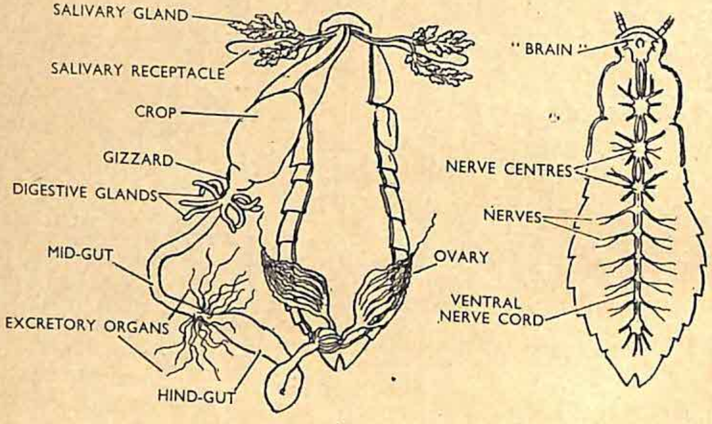


FIG. 93. A—Digestive and reproductive systems of female cockroach.
B—Nervous system (dorsal view).

food is then pushed into its mouth and down a short *gullet* into the large thin-walled '*crop*'† where digestion begins (see Fig. 93). The food then passes on to the '*gizzard*', a small, round, muscular organ that grinds up the food with the help of a ring of six horny 'teeth'. (N.B. The 'crop' and 'gizzard' of an insect do not correspond to those of a bird.) From the 'gizzard', the finely-divided food enters the *mid-gut*,† where it is mixed with digestive juices supplied by seven or eight finger-like digestive glands that open into the mid-gut. Digestion and absorption are completed in the mid-gut and the waste food residues then pass along the *hind-gut*† to the anus.

Where the mid-gut joins the hind-gut are numerous yellowish, thread-like *excretory organs*, which remove soluble waste material from the blood in the body-cavity.

THE RESPIRATORY SYSTEM

Insects breathe by means of *air-tubes* that extend throughout the animal. In a cockroach, air enters through the ten pairs of *breathing pores* into two main air-tubes running the length of the body, and these send off branches to every part.

The air-tubes carry oxygen to the tissues and remove carbon dioxide formed during respiration. Body-movements keep the air in movement throughout the whole system of branching air-tubes. Muscles contract and reduce the size of the body-cavity so that air is forced out through the breathing pores. When these muscles relax, the body-cavity expands again, and air is forced in owing to the higher pressure of the outside air.

THE BLOOD SYSTEM

In the cockroach, since air is carried to every part of the body by the air-tubes, the blood system can be very simple, for it is only concerned with carrying dissolved food. The blood itself is colourless. The '*heart*' is a long tube, running the length of the body on the dorsal side of the body-cavity. Blood from the body-cavity enters the heart and, when the heart 'beats', this blood is driven forward and delivered to the organs and tissues once more. A blood system of this kind is called an '*open circulation*', because the blood is not confined in a continuous system of blood-vessels as in the '*closed circulation*' of a mammal.

THE NERVOUS SYSTEM

A *ventral nerve-cord* lies below the food-canal (see Fig 93). This nerve-cord is double and forms a pair of *nerve-centres* (swellings containing nerve-cells) in almost every segment. From each of these swellings, nerve-fibres go out to the body-organs. In the head, the two halves of the nerve-cord form a 'collar' round the gullet and end in two larger nerve-centres, forming a primitive 'brain'.

Mosquitoes belong to a very large group of insects—the two-winged flies—in which only the front pair of wings develop fully, the hinder pair of wings being reduced to a pair of tiny projections or 'balancers'. Mosquitoes are found all over the world in great numbers and many varieties—over 1,500 different kinds being known to scientists. But practically all these different species fall

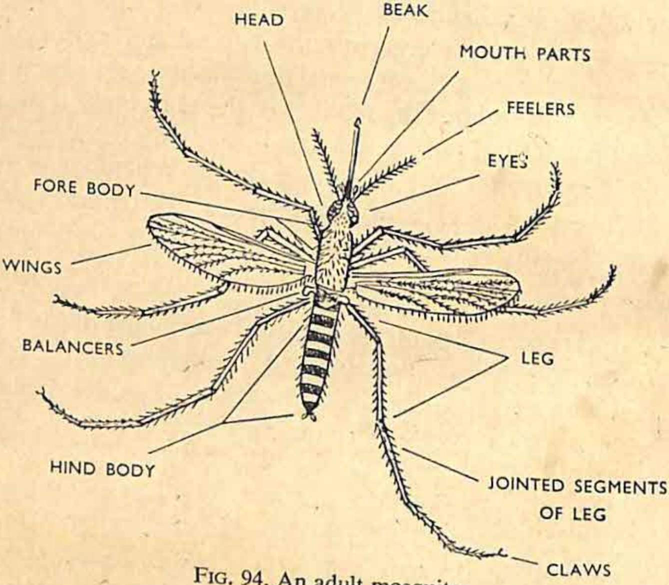


FIG. 94. An adult mosquito.

into two main groups: (i) the *culicines*† (commonly called 'gnats'†), and (ii) the *anophelines*† (commonly called 'mosquitoes'). As some anopheline mosquitoes can transmit the *malaria*† *parasite* they are very important in tropical countries, and we shall describe *Anopheles*† as an example of this group of insects.

EXTERNAL CHARACTERS

As in other insects, the body of an *anopheline mosquito* consists of *head*, *fore-body*, and *hind-body* (see Fig. 94).

The *head* has the usual pair of *compound eyes* and a pair of long, jointed *feelers*, bushy and hairy in the male, thinner and less hairy in the female. Projecting from the front of the head is the '*beak*' that distinguishes mosquitoes from other insects. This 'beak' is made up of a number of mouth parts corresponding to those of the cockroach, although very different in appearence. The 'beak' of a *male* mosquito consists of a slender tube and is used for sucking juices from *plants* (but *not* for sucking blood). The *female* mosquito, however, besides having a sucking tube for plant juices, also has inside the 'beak', a set of six needle-like mouth parts which are used to pierce* the skin and suck the blood of *animals*—including human beings (see Fig. 96). Only the female mosquito sucks blood.

The *fore-body* bears *three pairs of jointed legs*, and *one pair of wings*, together with a pair of tiny '*balancers*'. (The legs are used mainly for *resting* and not for movement, as a mosquito usually flies from place to place.)

The *hind-body* consists of ten segments, of which only eight can be readily distinguished.

LIFE-HISTORY OF MOSQUITO

The mosquito undergoes *complete metamorphosis* in its life-history. The *female Anopheles* lays anything up to 300 eggs, one by one, on a water surface. Each egg is shaped rather like a boat, and has a small *float* on either side that helps to keep the egg on the surface of the water (see Fig. 95).

About forty-eight hours later, the egg hatches out into a *larva* (or *wriggler*)†, with a distinct head, fore-body, and hind-body (see Fig. 95). In its early stages the young larva absorbs dissolved oxygen from the water and feeds on suspended food-particles, growing rapidly. About twenty-four hours after hatching, the young larva casts its skin. It repeats this process of feeding, growing, and skin-casting four times. During the later stages, the anopheline larva breathes air through a pair of *breathing pores* on the eighth segment of the hind body, lying in a horizontal position

below the surface film while breathing, and feeding with the help of its *mouth brush*.

After the fourth skin-casting and between one and two weeks

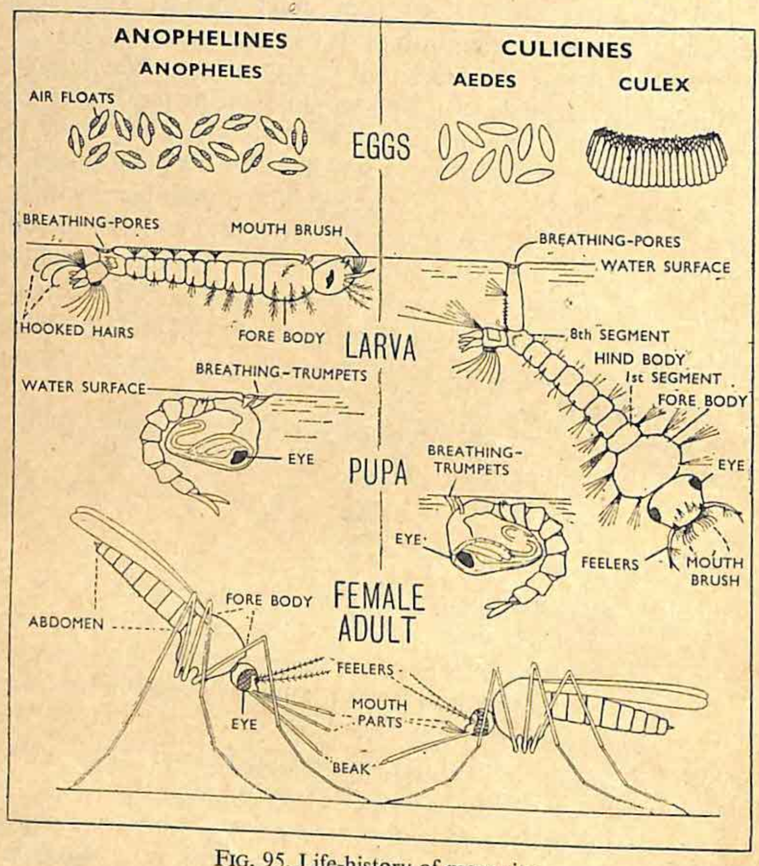


FIG. 95. Life-history of mosquito.

after hatching, the larva becomes a comma*-shaped *pupa*, with a large head and fore-body (see Fig. 95). This is a *resting stage* during which the legs, wings, feelers and mouth parts of the adult insect are developing. The pupa does not feed; but it rests tail downwards

beneath the surface film, breathing air through a pair of cone-shaped *breathing trumpets* that project from the head end (see Fig. 95).

After a couple of days as a pupa, the adult insect (or *imago*) emerges.* The insect rests on the surface of the water while its

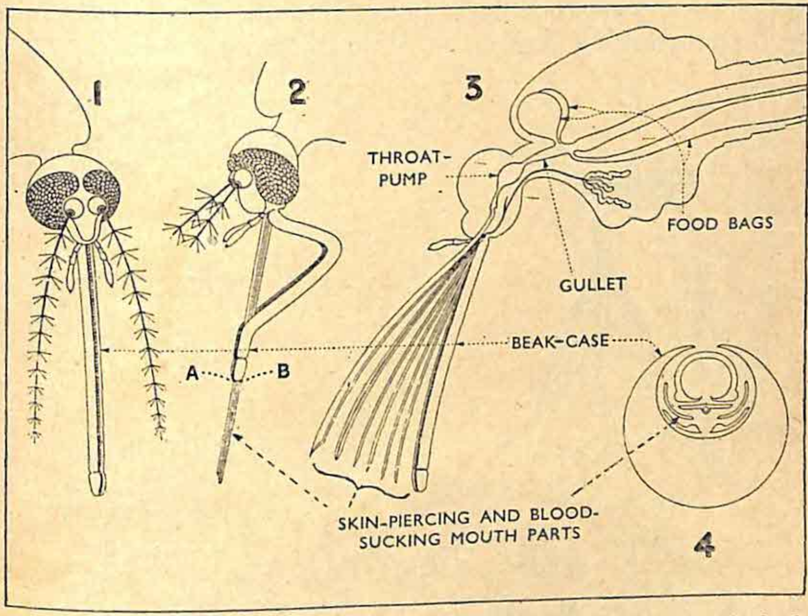


FIG. 96. Mouth parts of female mosquito. Highly magnified and showing the beak (1) at rest, (2) during the act of biting, (3) with the mouth parts separated, (4) in cross-section.

(In 2, the dotted line A–B indicates the surface of the victim's skin.)

wings expand and harden, and the mosquito then flies away. Mating takes place soon afterwards.

The adult Anopheles rests in a sloping position so that its body and beak are in one straight line, making an angle of 30–40° with the resting surface. Culex† rests with its body parallel to the resting surface (see Fig. 95).

The female Anopheles has to suck blood if her fertilized eggs are to develop, and as she digests the blood, the eggs develop. To obtain this blood, the beak and its needle-like mouth parts are forced through the victim's skin (see Fig. 96). Liquid from the insect's *salivary glands* is then squirted into the wound to stop the blood from clotting, and to break up the red blood-cells, which

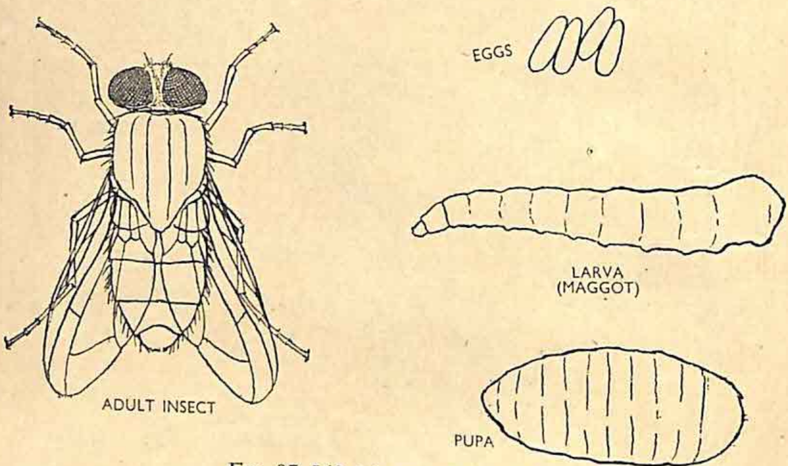


FIG. 97. Life-history of house-fly.

are too big to pass through the 'beak'. Then the blood is pumped up and passed into the insect's 'stomach'. If the victim is suffering from *malaria*, his blood contains microscopic, one-celled *malaria parasites*, and some of these are sucked up with the blood and enter the insect's 'stomach'. Here the parasites pass through some stages of their life-history and then, after 9–12 days, find their way into the mosquito's salivary glands. If this mosquito then bites another victim, these malaria parasites are passed into his blood and he is infected with malaria. (The life-history of the malaria parasite is described in more detail in Book IIIA.)

Fig. 97 illustrates the stages in the metamorphosis of the common

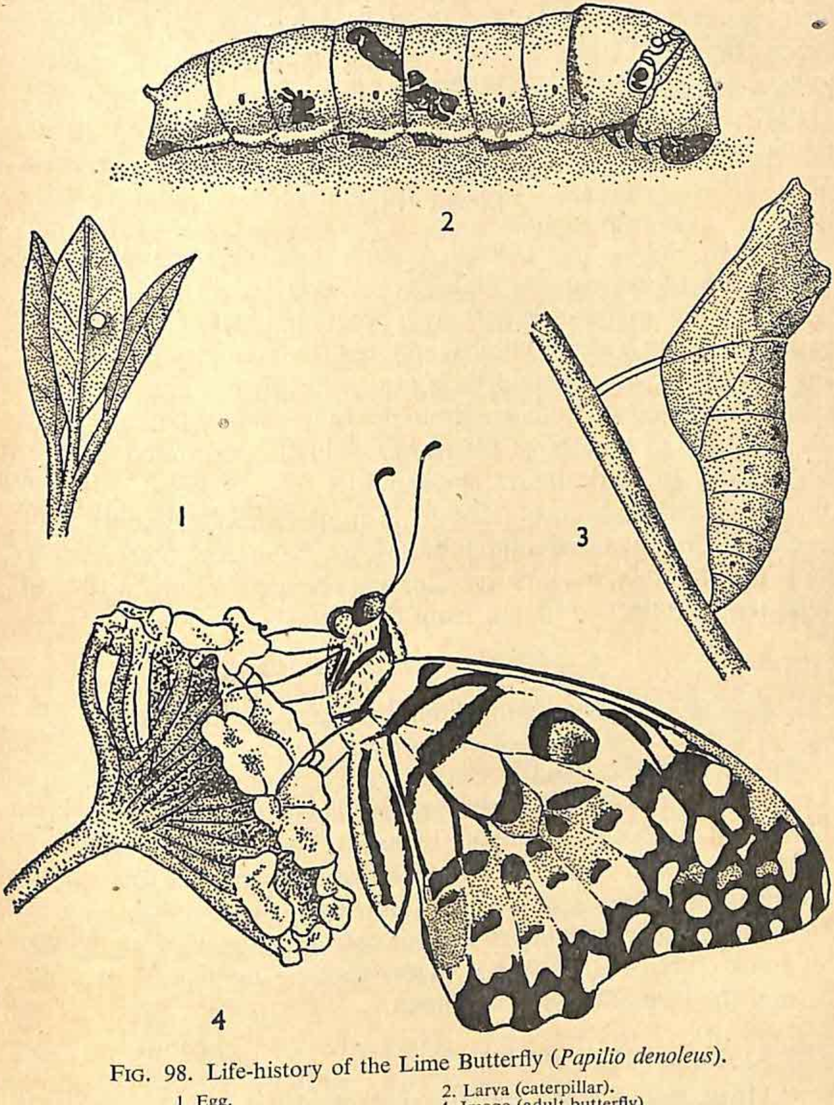


FIG. 98. Life-history of the Lime Butterfly (*Papilio denoleus*).

1. Egg.
2. Larva (caterpillar).
3. Pupa (chrysalis).
4. Imago (adult butterfly).

house-fly. This lays its eggs in animal manure, in which the larvae (maggots†) develop. The whole life-cycle—egg, larva, pupa, imago, egg—occupies less than two weeks.

Fig. 98 illustrates the stages in the metamorphosis of a common tropical butterfly.

MOLLUSCS

At this point on the 'ladder of life' it is difficult to say whether one group of animals is 'higher' or 'lower' than another, since some of them are built on entirely different plans. For example, the insects, with their jointed limbs (adapted for movement or for feeding or as sense-organs) and their external skeleton, are among the most specialized and efficient animals. In insects we find a remarkable method of breathing, the power of flight, and much 'division of labour'. In some insect communities, e.g. of bees, ants, and termites, this 'division of labour' is more complicated than the social* life of any other animal but Man. The insects, therefore, are one of Nature's most successful experiments along a line of adaptation entirely different from that of other animals.

MOLLUSCS

Judged by the development of their nervous system, the *Molluscs*† are the 'highest' of the *Invertebrates*—the backboneless animals. They are also the second largest group of animals, numbering over 60,000 different species. There are three important classes of molluscs, examples of each class being the *snail*, the *oyster*,† and the *octopus*.† The body of a mollusc is not divided into segments, and there are *no limbs*. The molluscs are *soft-bodied*, but the skin forms a protective shell of calcium carbonate that serves as an external skeleton. We shall study a land-snail as a representative of the largest class of molluscs.

THE GIANT* SNAIL (ACHATINA†)

In its expanded condition, the snail carries its spiral shell on the middle of its back with the tip of the shell turned to the right (see

Fig. 99). The upper part of the shell is occupied by some of the digestive organs, while the lower part can hold the entire animal when the snail withdraws itself inside its shell. The growing edge, or *lip*, of the shell is surrounded by a thick, muscular *collar*. As the animal grows, additions are made to the lip of the shell, so that the shell grows with the snail and there is no need for the skin-casting that is a characteristic feature of the insects and similar arthropods (boneless animals with jointed limbs).

In the snail's expanded condition, the part of the body outside the shell is somewhat oval* in shape, with a thick, muscular '*foot*'. At the anterior end of the body is the *mouth*, bounded by a pair of side lips and a small, horizontal, under-lip. Beneath the mouth is the

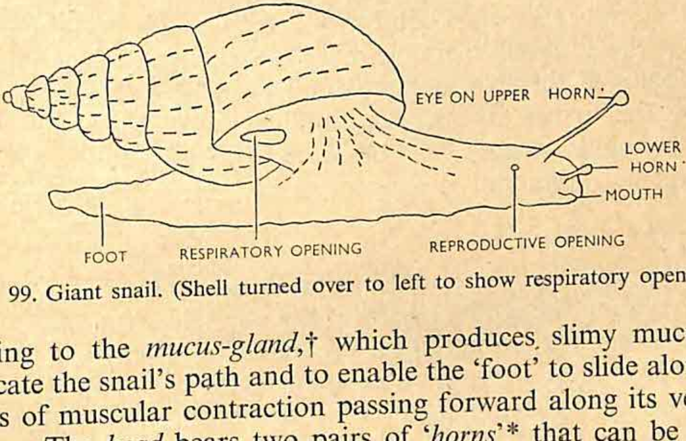


FIG. 99. Giant snail. (Shell turned over to left to show respiratory opening.)

opening to the *mucus-gland*,† which produces slimy mucus to lubricate the snail's path and to enable the 'foot' to slide along by waves of muscular contraction passing forward along its ventral surface. The *head* bears two pairs of '*horns*'* that can be withdrawn inside the body. The upper 'horns' are the larger and bear *eyes*. Just behind the right eye-horn is a small *reproductive opening*.

THE DIGESTIVE SYSTEM

The Giant Snail feeds on the soft, green parts of plants, rubbing its file-like '*tongue*' against its horny upper 'jaw' and thus 'chewing' its food. In the mouth, the ground-up food is mixed with *saliva* produced by a pair of *salivary glands*. It is then passed down the

gullet to the wide, thin-walled '*crop*', and from thence to the '*stomach*' and *intestine*. The coils of the intestine are embedded in the '*liver*', which occupies the upper part of the shell. The undigested food residues are finally got rid of at the *anus*, a small opening inside the collar, near the *respiratory opening* (see Fig. 210).

THE RESPIRATORY SYSTEM

Inside the collar is a large, round *respiratory opening* that alternately opens and closes, admitting air to the *mantle*†*-cavity*, a primitive *lung*, whose roof is formed by a fold of skin (the *mantle*), richly supplied with blood flowing in a network of blood-vessels (see Fig. 210).

The muscles forming the floor of the mantle-cavity alternately contract and relax, thus continually changing the air in the 'lung'.

Oxygenated blood from the mantle is carried to the heart and is then pumped through arteries to all parts of the body, where it bathes the tissues. The snail's blood is translucent* and slightly blue in colour owing to the presence of dissolved *haemocyanin*,† an organic compound of copper, which acts as an oxygen carrier.

THE NERVOUS SYSTEM

In the ringed worms and the arthropods there is a ventral nerve-cord running the whole length of the animal, with a *nerve-centre* in each segment. In molluscs, the nervous system is much more centralized into nerve-centres, there being three chief pairs of nerve-centres linked together by nerves. One pair controls the head, another pair controls the 'foot', and the third pair controls the internal organs.

THE REPRODUCTIVE SYSTEM

Like earth-worms, snails have both male and female reproductive organs in the same animal, hence the reproductive system is too complicated to discuss at this point (see Book Four, Chap. X).

All the animals we have studied up to this point in the 'ladder of life' have been *Invertebrates* or *backboneless animals*. We shall now

deal with the other great division of animals, the *Vertebrates* or *backboned animals*.

ANIMALS WITH BONES—VERTEBRATES

VERTEBRATES

The animals we have studied so far, in this Chapter, have been *soft-bodied*, although some of them have a hard *outer* covering. This outer layer is their only hard tissue, and the arthropods live inside an *external* skeleton built up of jointed hollow tubes. The 'highest' animals, however, have a hard, *internal*, bony framework or *skeleton*, to support their bodies, and the animals in this important group are called *Vertebrates*. The group includes all the larger animals, namely *fishes*, *amphibians*† (e.g. frogs and toads†), *reptiles*† (e.g. snakes and lizards†), *birds* and *mammals*.

The main characters that distinguish Vertebrates from Invertebrates are:

INVERTEBRATES	VERTEBRATES
If there is a nerve-cord, it is *ventral* to the food-canal.	The brain and spinal cord are *dorsal* to the food-canal.
If there is a skeleton, it is *external*.	There is an *internal* skeleton with its main axis (the backbone) dorsal to the food-canal.
If there is a heart, it is *dorsal* to the food-canal.	The heart is *ventral* to the food-canal.

In all Vertebrates, the blood has haemoglobin confined* within red blood-cells, and they all have liver, pancreas, spleen, and kidneys.

The most primitive living Vertebrates (apart from *lampreys*†) are the *fishes*, and their fossil remains show that they have been the most successful water-living animals from very early times up to the present day. The *amphibians* were fairly numerous in the early days of the first land-animals, and *reptiles*, the next higher stage,

were once the dominant animals on the Earth. All members of these three groups—fishes, amphibians, and reptiles—are '*cold-blooded*' or '*variable-temperature animals*'. Nowadays, the amphibians and reptiles are of less importance, and the dominant land-animals are the 'warm-blooded' birds and mammals. The fishes, however, still remain 'the masters of the sea' as they seem to have been before amphibians and reptiles took to life on land.

COLD-BLOODED VERTEBRATES

FISHES

During their very long history, fishes have evolved into many different forms. There are three main groups of fishes, (*a*) the more primitive fishes with their skeletons composed mainly of *gristle*, e.g. sharks,† (*b*) the 'true fishes' with a *bony* skeleton, e.g. carp,† and (*c*) the 'lung' fishes (which form only a very small group).

The general shape of a fish is that of a cigar. This is the best shape for moving through water, as there are neither neck nor projecting parts to break the smooth, curved outline. (Man has used this 'streamline' shape in submarines, airships, aeroplane-bodies, racing motor-cars, and racing motor-boats.) In addition, the skin is covered with characteristic overlapping *scales*,† which are kept slimy, thus forming a very smooth body-surface. The average density of a fish is nearly the same as that of the water in which it lives, so that its whole weight is supported by the up-thrust of the water. Slight variations in the density of a bony fish can be made, however, by means of the *swim-bladder*, which lies just below the backbone and contains air (see Fig. 100). By varying the amount of air in the swim-bladder, the fish can adjust its average density. (Man adjusts the average density of submarines in exactly the same way.) The swim-bladder also keeps the fish in an upright position. (A dead fish, with no air in its swim-bladder, floats upside down.) Gristly fishes have no swim-bladder.

A characteristic feature of fishes is that they have *fins*, folds of skin stiffened by bony rods. These are of two kinds, *paired fins*, and

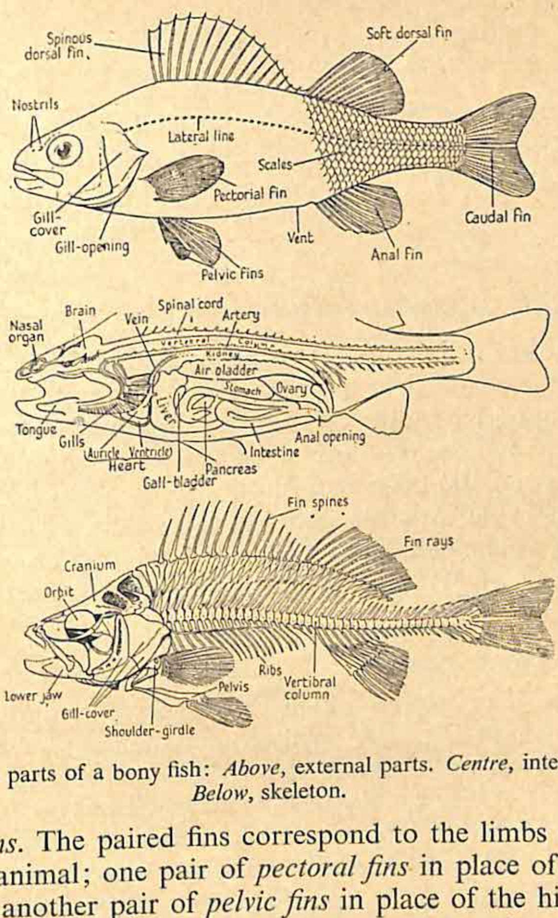


FIG. 100. The parts of a bony fish: *Above*, external parts. *Centre*, internal organs. *Below*, skeleton.

unpaired fins. The paired fins correspond to the limbs of a land vertebrate animal; one pair of *pectoral fins* in place of the fore-limbs, and another pair of *pelvic fins* in place of the hind-limbs. These paired fins are used mainly for balancing and steering, the fore-fins serving as horizontal rudders or as 'brakes'.

The unpaired fins are arranged along the dorsal and ventral surfaces of the fish and serve to keep the fish upright in the water (in the same way as the keel* of a boat). The *tail fin* (*caudal fin*†) helps to force the body through the water (see Figs. 100 and 101).

The *muscles* of fishes are very well developed; in fact, we find

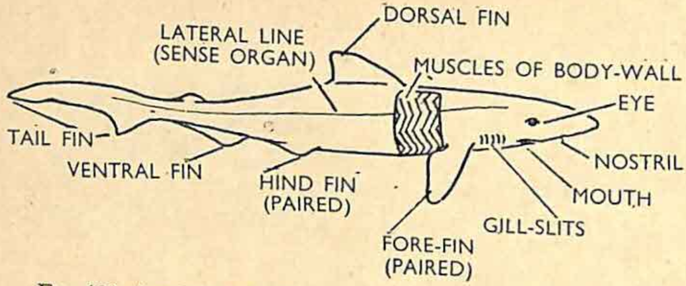


FIG. 101. A gristly fish—the Indian shark (*after Thillayampalam*).

more to eat in a fish than in any other animal of the same size and weight. Because of their powerful muscles, and because their weight is supported by the up-thrust of the water, fishes can swim very quickly and for very long distances, e.g. a *salmon*† has been known to swim 100 miles in 24 hours. *Eels*† swim from Western Europe across the Atlantic Ocean and lay their eggs around Bermuda. The young eels, after hatching, then swim eastwards back to the rivers of Western Europe, taking three years over the journey!

THE RESPIRATORY SYSTEM

On either side of the mouth-cavity are special respiratory organs called *gills*† (see Fig. 100). Water, containing dissolved oxygen, passes in through the mouth, over the gills, and out again through the *gill-slits*.† As the water passes over the gills, oxygen is absorbed by the blood in the gills, and at the same time carbon dioxide is given up to the water. The gills are split up into large numbers of tiny, thin plates, so as to expose as large a surface area as possible to the water. Although fishes appear to be 'drinking water', they are only passing it over their gills. A ring of muscle round the gullet keeps the entrance to the food-canal closed except when food is being swallowed. As in earth-worms, the oxygen is carried by haemoglobin, but this is not merely dissolved in the blood but it is confined within the *red blood-cells* as in all vertebrate animals. (In tropical countries, where the water is often too warm to dissolve

sufficient oxygen, many fishes are 'air-breathers', coming to the surface from time to time and filling an 'air-chamber' above the gills with air.)

Fishes have a simple *two-chambered heart* that pumps blood received from all parts of the body to the gills and then to the various parts of the body. Thus, in a fish, the blood goes only *once* through the heart in each complete circuit.* (In mammals there is a double circulation. Blood from one side of the heart is sent round the *body* and then returns to the other side of the heart to be pumped to the *lungs*; i.e. the blood passes through the heart twice in each complete circuit.)

THE DIGESTIVE SYSTEM

The mouth of a fish has *teeth* and two *jaws*, both top and bottom jaws being movable.

Some fishes feed on plants, and others on water-animals, including smaller fishes. The food is seized with the teeth and passed down the throat into the gullet. Comb-like structures called *gill-rakers*† prevent food from being lost through the *gill-slits* on the way. The general arrangement of the digestive system is very similar to that of the frog, which is the next animal we shall study.

THE NERVOUS SYSTEM

The nervous system in fishes is also very similar to that in the frog.

The *eyes* of a fish have only single lenses, as in all the vertebrates. Eyelids are usually absent, but the eye is covered with a transparent membrane. The *hearing organs* are under the skin, but a fish's sense of hearing is very good, since sound travels through water better than through air. Fishes have *nostrils*, although they do not open into the mouth and are not used for breathing: they are used only for smelling and tasting the water.

THE REPRODUCTIVE SYSTEM

Like all Vertebrates, fishes are either male or female. The *egg-cells* produced by the *female* are fertilized by *sperms*† produced by

the *male* fish. In some fishes, the fertilized eggs develop outside the body of the parent, hatching after a time. In such cases the newly-hatched young fishes usually have some of the egg-yolk still attached to their bodies, and they feed on this during the early part of their life. In other fishes, the fertilized eggs develop inside the body of the female parent, and the young are born alive at a stage when they can look after themselves. When eggs are passed out just before or just after fertilization, there is a very high death-rate, and most of the eggs are wasted. The method of producing the young alive at a more advanced stage of development greatly reduces this wastage.

THE SKELETON

In the primitive fishes, like the dogfish† or shark, the skeleton is composed of *gristle*, while the 'true fishes', e.g. the carp, have a bony skeleton (see Fig. 100). The general arrangement, however, is similar in both groups. There is a main axis consisting of *skull* and *backbone*. The backbone consists of a large number of jointed *vertebrae*, some of which bear *ribs*. (The vertebrae show that a fish is a 'segmented animal'. The body-muscles are also arranged as V-shaped segments as shown in Fig. 101.) The fish skull is very similar to that of the frog. The paired fins are attached to limb-girdles (except that bony fishes have no 'hip-girdle'). We shall discuss the *scales* of fishes in Book Four, Chap. VIII.

AMPHIBIANS—THE FROG

The most primitive *land*-animals that have a bony internal skeleton are the *amphibians* (e.g. frogs and toads), so called because the first part of their life-history is spent in water and the second part on land.

In the history of living things on the Earth, the *amphibians* were the first animals to begin to colonize the dry land. Before the appearance of the amphibians, animal life in the world was restricted to water. Fossil remains show that in the forests from

which our present coal deposits were formed there were many kinds of amphibians, in fact they were the only backboned land-animals at that time. Nowadays the race of amphibians has lessened in numbers and in size. Very few modern amphibians exceed *six inches* in length, but some of their ancestors in the time of the coal-forming forests were *six feet* in length.

The frogs and the toads are the most successful amphibians today.

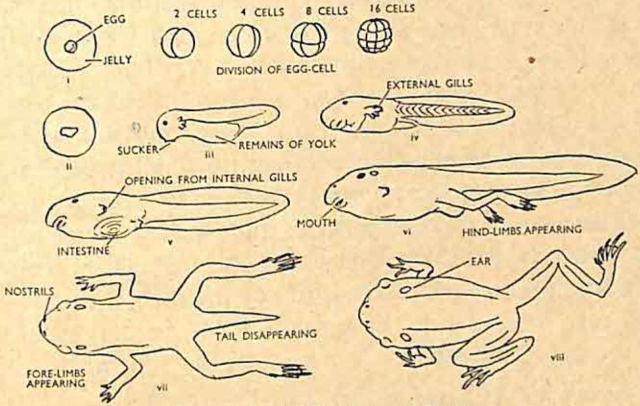


FIG. 102. Life-history of frog.

LIFE-HISTORY OF THE FROG

Although frogs spend the greater part of their life on land, they usually have to return to water to breed. With the exception of a few tropical frogs, the female frog lays her *eggs* in water, where they are *fertilized* by *sperms* poured over them by the male frog (as the eggs pass out of the female's body into the water). Each tiny *egg* is spherical in shape, the top half being black and the lower half white; it is enclosed in a much larger sphere of clear jelly (see Fig. 102 (i)). This jelly is distasteful to other animals, which would otherwise eat the eggs, and it also protects the delicate *embryo* while still allowing room for its growth. After fertilization, the one-celled egg divides, first into two, then into four, eight, sixteen, and thirty-two

cells, and so on; without, however, growing very much in size at this stage (see Fig. 102 (i)). During this division (which is a good example of increase in *cell-number* during *growth*) the black region at the top of the egg spreads downwards over the rest of the egg.

At this early stage, all the cells of the embryo are alike. Later they become very different from one another in appearance and function, e.g. some become muscle-cells, some become nerve-cells; others become reproductive cells, and so on.

This round ball of cells soon becomes oval and then grows in length. At this stage, using a hand-lens, we can see a pair of ridges with a groove between them, running along the back of the embryo. This is the beginning of the *central nervous system*—brain and spinal cord. Signs of a definite head, body, and tail soon appear, and the embryo curls up inside its covering of jelly (see Fig. 102 (ii)).

The young *tadpole*† then hatches out and escapes from the jelly. Fig. 102 (iii) shows a newly hatched tadpole, which then attaches itself to a water-plant. At this stage, the tadpole has no mouth, although small pits mark the position of the future mouth, nostrils, eyes and ears. Meanwhile the tadpole feeds on the remains of the yolk of the egg. The anus can be seen on the ventral surface of the body near the base of the tail.

The next stage shows a number of important changes. The mouth opens and the tadpole can feed on water-plants. Three pairs of feathery *external gills* appear on either side of the hinder part of the head, and by means of these gills the tadpole absorbs oxygen from the water (see Fig. 102 (iv)). At this stage, too, the *food-canal* grows so long that it becomes rolled up in a spiral, something like a watch-spring. It is clearly visible from the ventral surface through the thin, transparent, body-wall.

Another distinct stage is reached when a fold of skin grows backwards from the sides of the head to form a *gill-chamber* covering the external gills, which later wither away as they are replaced by a new set of *internal gills*. The tadpole takes in water through its mouth, passes it through the *gill-slits*, over the external gills and out again through an opening at one side of the gill-chamber, thus

absorbing the oxygen necessary for respiration, as a fish does. During this stage the tadpole's jaws become horny and it feeds greedily on plants, increasing rapidly in size (see Fig. 102 (v)).

The next distinct stage is reached when the *limbs* begin to appear as small projections under the skin.

The *hind-limbs* appear first (see Fig. 102 (vi)), while the *fore-limbs* take longer to break through (see Fig. 102 (vii)). At this stage also, the *lungs*, which have been developing slowly for some time, are brought into use, and the tadpole rises to the surface of the water from time to time and fills its lungs with air. For a short time the tadpole uses both gills and lungs, but as the lungs develop the gills wither away. At the same time, the structure of the mouth changes; the horny jaws are cast off, the rounded mouth becomes much wider, and the small tongue grows rapidly in size. While these changes are going on, the tadpole stops eating water-plants and its tail gradually disappears (for it has now become a source of food). Metamorphosis is now complete, and the fish-like, plant-eating tadpole has become an air-breathing, land-living, carnivorous frog.

THE ADULT FROG

The body of an adult frog consists of head and trunk (see Fig. 102 (viii)). There is no neck, the head being joined directly to the trunk, and there is no tail. The skin is smooth, damp, and loose-fitting. The head is flattened and roughly triangular in shape, and bears a pair of projecting *eyes* (each with three eyelids), and a pair of *nostrils* placed in such a position that the animal can see and breathe while the rest of its body is under water. Just behind each eye is a round patch of stretched skin—the frog's *ear-drum*. The slit-like *mouth* is very wide, and there are small teeth along the upper jaw and on the roof of the mouth. (Toads have no teeth.) A long, sticky *tongue* is attached to the *front* of the lower jaw and can be shot out very quickly to capture the small animals on which the frog feeds.

Each *fore-limb* consists of an *upper arm*, a *lower arm*, a *wrist*, and a *hand* of four fingers but no well-marked thumb. The *hind-limbs*

are much longer than the fore-limbs and consist of a *thigh*, a *leg*, an *ankle*, and a *foot* with five toes, joined together by *webs** of skin. The amphibians were the first animals to develop *five-fingered* limbs, with the backward-pointing *elbow* and the forward-pointing *knee* that are characteristic of all land vertebrates.

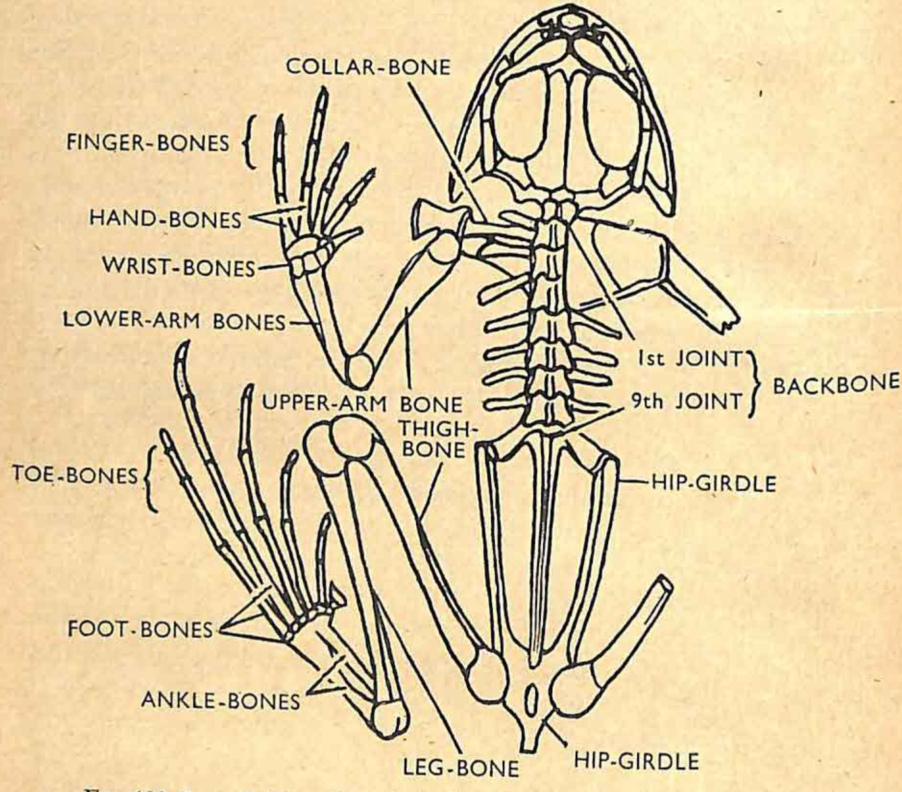


FIG. 103. Frog skeleton (dorsal view). Only one shoulder-blade is shown.

THE FROG'S SKELETON

The frog's skeleton is an internal framework of *bone* and *gristle*, and it consists of a skull and backbone, together with the bones of the four limbs (see Fig. 103). The middle of the skull consists of a

small *brain-case*, enclosing and protecting the brain. Anterior to this are two *nose-cases* enclosing the organs of smell, and on either side of the back of the skull are two *ear-cases* enclosing the organs of hearing. The *upper jaw* is attached to these nose- and ear-cases, and the *lower jaw* is hinged to the back of the skull. The skull is attached to the *backbone*, which encloses and protects the *spinal cord*. The backbone consists of *nine joints* (or vertebrae) and one long, unjointed bone at the hinder end. The first vertebra is attached to the skull, and the others are joined together by 'ball-and-socket' joints. The frog has no fully developed ribs. The *hind-limbs* arise from the 'V'-shaped *hip-girdle*, which is firmly attached to the backbone, and each *thigh-bone* is joined to this hip-girdle by a 'ball-and-socket' joint. The *leg-bones* are hinged to the lower ends of the thigh-bones, and the *ankle-bones* in turn are also hinged to the leg-bones. The *foot* consists of a number of jointed *foot-bones* with *five toes*.

The *fore-limbs* arise in the same way from the *shoulder-girdle*, which is not attached directly to the backbone but is embedded in the muscles of the body-wall. The *upper-arm bone* corresponds to the thigh-bone, the *lower-arm bones* correspond to the leg-bones, while the *wrist-bones*, though very much shorter, correspond to the ankle-bones. The '*hand*' is made up of a number of jointed bones, with *four fingers* and hardly any thumb.

It is very noticeable that the hind-legs of a frog are much longer than the fore-limbs. These long hind-legs give great leverage for jumping, and all animals that jump (e.g. kangaroo, grasshopper†) have very long hind-legs.

The *muscles* consist of bundles of muscle-fibres attached to the bones by *tendons*.

THE FROG'S DIGESTIVE SYSTEM—THE FOOD-CANAL

Food captured by the animal is forced down the *gullet*, a short, wide tube, into the *stomach*, a still wider tube (see Fig. 104). Glands in the wall of the stomach produce *gastric juice*, which begins the digestion of the food, forming a soft mixture that is passed on into

the *small intestine*, a narrow, coiled tube, the longest part of the food-canal. *Bile*, produced by the *liver*, a large, reddish-brown organ, and stored in the *gall-bladder*, a small, round, green sac, is passed along a duct into the first part of the small intestine. *Pancreatic juice*, another digestive fluid, is formed in the *pancreas*, a pink gland lying between the stomach and the small intestine, and is also passed through the bile duct into the intestine. Glands in the

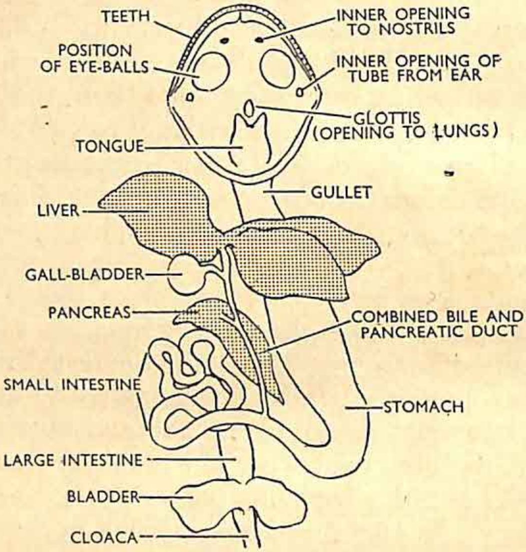


FIG. 104. Food canal of frog (diagrammatic—*after Hatfield*).

wall of the small intestine produce another digestive fluid—*intestinal juice*. By the action of all these digestive juices, the food is *digested* and converted into simple, soluble substances that are *absorbed*, diffusing through the thin walls of the small intestine into the blood. From the small intestine the undigested residue is passed on to the *large intestine* where some water is absorbed before the *faeces* are got rid of through the *cloaca*.† (When the food-canal, the excretory ducts, and the reproductive ducts all share one posterior opening, this common opening is called a *cloaca*. When

the food-canal has its own separate posterior opening, as in mammals, this opening is called an *anus*.)

HOW A FROG BREATHES

The 'highest' land-animals—birds and mammals—breathe only by means of their *lungs*. Although a frog has lungs, they are not as efficient as those of birds and mammals, and the frog does not depend on them entirely for absorbing oxygen. Besides *lung-breathing*, a frog also gets oxygen for respiration through its *skin* and by *mouth-breathing*. The frog's skin has a special blood supply and contains a network of capillary blood-vessels, so that oxygen dissolved in the water on the damp skin is absorbed by the blood in these capillaries, and carbon dioxide is given up at the same time. In cool, damp surroundings, a resting frog can absorb sufficient oxygen through its skin to keep alive.

A more active frog, requiring more oxygen, takes in air through its nostrils and makes use of *mouth-breathing*, and under still more active conditions, of *lung-breathing*. The mouth is *kept closed*, the nostrils are opened, and the floor of the mouth is lowered, thus enlarging the volume of its cavity, so that air enters. (In fact, a frog suffocates if its mouth is kept open.) Oxygen and carbon dioxide are exchanged between the air and the blood in the capillaries of the walls of the mouth-cavity, and the used air is then forced out through the nostrils. In order to use its lungs as well as its mouth for breathing, the frog first fills its mouth with air by lowering the floor of its mouth, closes its nostrils, and then, by raising the floor of its mouth once more, forces air down the *windpipe* into the lungs, which are two oval, transparent sacs, where exchange of gases takes place.

To breathe out, the lungs are compressed and air is forced back to the mouth and out through the nostrils.

THE FROG'S BLOOD SYSTEM

The frog's *heart* is a hollow cone-shaped bag of muscle, divided into *three chambers*—a *right auricle*, a *left auricle*, and a single,

thick-walled *ventricle*. De-oxygenated blood from the *body-circulation* enters the *right auricle* while oxygenated blood from the *lung-circulation* enters the *left auricle*. As the two auricles contract, both kinds of blood are forced into the *ventricle*, but there is very little mixing owing to the spongy structure of the ventricle. Hence, when the ventricle is full, its left side contains *oxygenated blood*, its right side contains *de-oxygenated blood* and there is a little *mixed blood* in the middle. When the ventricle contracts, blood is forced into the *main artery*, which branches and sends blood to the lungs and to all parts of the body. The three main arteries on each side, however, are arranged in such a way that (*a*) *de-oxygenated blood goes to the lungs and skin*, (*b*) *mixed blood goes to the hinder part of the body*, and (*c*) *oxygenated blood goes to the head and brain.*

The frog's blood consists of oval *red cells* (containing *haemoglobin*) and rather fewer *white cells*, floating in a colourless liquid. This colourless liquid escapes through the thin walls of the capillary blood-vessels and forms the *tissue-fluid* that bathes every living cell, carrying oxygen and food from the blood to the cells, and carbon dioxide and other waste products from the cells to the blood. This 'used' tissue-fluid, or *lymph*, is then collected by small *lymph-vessels* into large and numerous *lymph-sacs*, mostly lying between the skin and the body-wall. All the lymph-sacs are connected with each other, and two pairs of *lymph-hearts* pump the lymph back into the veins.

THE FROG'S EXCRETORY SYSTEM

Carbon dioxide and some water are got rid of through the lungs and skin. Urea and water are removed from the blood by the *kidneys*, two long, flattened, red organs, situated just ventral to the backbone. This *urine* drains into the *bladder* and is passed out from the *cloaca* at intervals.

THE FROG'S NERVOUS SYSTEM

The frog's *central nervous system* consists of the *brain* and the *spinal cord*. The brain lies inside the bony *brain-case* and gives off

cranial† *nerves*, nearly all of which supply the sense-organs and muscles of the head-region. The spinal cord arises from the posterior end of the brain and runs through the bony tube formed by the backbone, giving off *spinal nerves* that supply the muscles and skin of all parts of the body except the head.

REPTILES

The *amphibians* are dependent on water during the early stages of their life-history, and require damp conditions throughout their adult life, hence they only live near water. The *reptiles*, e.g. snakes,

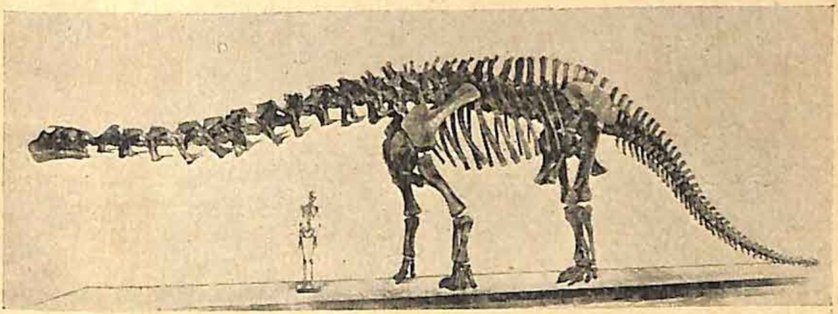


FIG. 105. Skeleton of giant reptile that lived millions of years ago (with skeleton of present-day man for comparison).

lizards, crocodiles,† turtles,† and tortoises,† were the first back-boned animals to become independent of such conditions. At one stage of the Earth's history, the reptiles were the most successful group of animals. Their conquest of the dry land was no doubt aided by the development of dry scaly skins and of shell-covered or tough-skinned *eggs* with large yolks. When the reptiles reached their greatest success, some of them grew to a length of 100 feet and to a height of 20 feet (see Fig. 105).

WARM BLOODED ANIMALS

Two kinds of more efficient animals evolved later than the reptiles, namely the *birds* and the *mammals*. These have the advantage

of being 'warm-blooded' animals, being able to control their body-temperature in a way that is impossible to the 'cold-blooded' reptiles and amphibians. Snakes and frogs are only active under warm conditions and are therefore commonest in tropical countries. In countries with a cold season, snakes and frogs become inactive as the temperature falls, and they rest quietly until warm weather returns and their bodies become warm enough to carry on the living processes more rapidly. Also, birds and mammals make careful provision for their young, both before and after hatching or birth. Possibly as the result of these more efficient features, birds and mammals have become the most successful groups of animals on the Earth, just as fishes have become the dominant animals in the waters on the Earth's surface.

BIRDS

The birds were able to spread all over the world because of their power of *flight* and because their blood is warm (100–110° F.). To help in keeping the blood at a constant temperature, birds have a non-conducting layer of *feathers* that stops loss of heat from the body under cold external conditions. The power of flight, besides enabling birds to escape from their enemies, also enables them to *migrate** from one region to another when conditions become unfavourable, e.g. during the warmer season the animal life of the Polar regions consists almost entirely of birds, but these birds migrate to a more favourable climate before winter.

EXTERNAL CHARACTERS OF BIRDS

Birds show a number of special characters, mostly connected with their power of flight. Their most characteristic feature is the production of *feathers*. This distinguishes birds from all other animals. Like the scales of reptiles and the hairs of mammals, feathers are produced by the skin. Each large feather has a central axis (or *quill*†) arising from a pit in the skin. The lower part of the quill is hollow and the upper part is solid. On either side of the quill is a *blade* consisting of a parallel row of sloping, narrow,

flexible branches called *barbs*† (see Fig. 106). Each barb bears two opposite rows of oblique* branches called *barbules*.† The barbules on one side of each barb are hooked, and they interlock* with the barbules on the next row of barbs, thus giving the blade a continuous surface, which is almost air-tight. The large quill-feathers

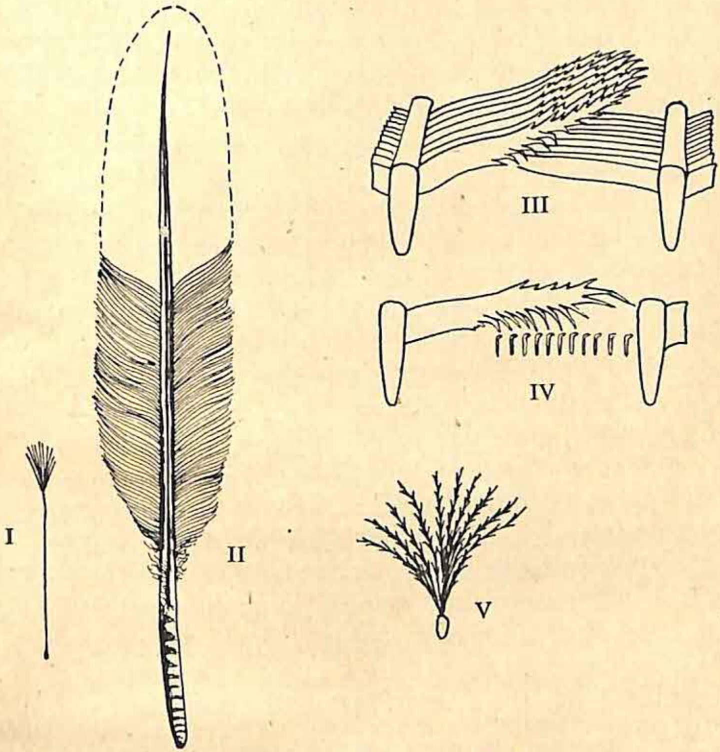


FIG. 106. Feathers of domestic fowl.

I = hair-like feather. II = quill-feather. III and IV = diagrams showing how barbs and barbules interlock. V = down-feather.

of the wings and tail are of this type. Smaller overlapping feathers of the same type cover the rest of the wings, the head, neck, and trunk, giving the body its smoothly curved outline. Hair-like feathers, with a few tiny barbs at their tips, are found among the

covering feathers described above. (These are left in the skin after a bird has been 'plucked', i.e. after the quill feathers and covering feathers have been pulled out.) Some birds, e.g. ducks,† also have soft, furry *down*-feathers*, but these are absent in pigeons.†

All these feathers are changed from time to time, usually after each breeding season. The bird casts its old feathers (or 'moults'†) and grows new ones from the same pits in the skin.

The quill-feathers of the wings overlap and form a flat surface for striking the air when the bird is flying. The quill-feathers of the tail are usually arranged like a fan and are very flexible, being used as a rudder during flight. The covering feathers can be made to lie flat against the body, or to stand out so as to enclose more air. When the feathers are held flat against the body, little air is enclosed between the feathers and the skin, and the non-conducting layer is thin. In cold weather, therefore, a bird raises its feathers so as to enclose more air and keep itself warm.

The neck of a bird is very long and very flexible. In fact, almost every part of the body can be reached by the beak. The head bears a characteristic horny structure—the *beak* (or *bill*†). There are many different types of beaks in different birds, adapted to different types of food and to different methods of life, e.g. the flattened beak of a duck for searching in mud for food; the curved beak of a parrot† to help in climbing; the hooked bill of a bird of prey* (e.g. eagle† or hawk†) for tearing flesh; the long, thin beak of a sun-bird or humming-bird for getting nectar from long, trumpet-shaped flowers; the long, thin beak of a snipe† for searching in mud for food; and the thick, short beaks of seed-eating birds (see Fig. 107).

The eyes are large, and are provided with three eyelids (as in the frog), the third eyelid serving to clean the front of the eyeball. Except in the case of owls† and birds of prey, the eyes are at the *sides* of the head, thus giving the bird a wider field of view and better protection from its enemies. Birds of prey do not 'need' this protection, and their eyes are directed to the front, where they can be most efficient in searching for food. There are no external ears;

but two ear-holes, just posterior to the eyes, lead to the internal ears. The nostrils are two holes on either side of the beak close to where it joins the head, and they lead into the mouth.

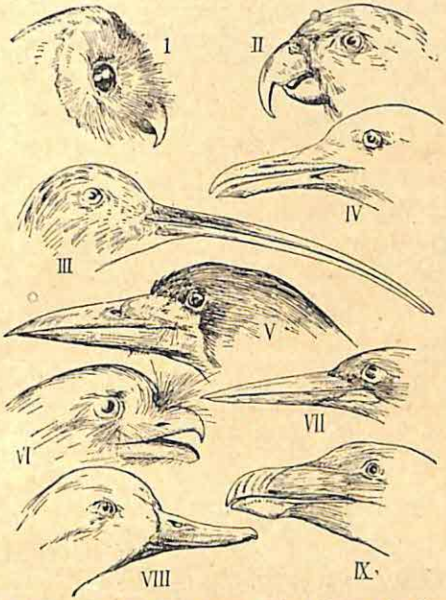


FIG. 107. Types of beaks adapted to different feeding habits.

ADAPTATION TO HABITS AND SURROUNDINGS

Although all birds are built on a very similar general plan, there are many small variations to suit varying habits and surroundings. We have already discussed modifications of beaks. Similar variations are found in legs and feet, e.g. the domestic fowl† has powerful feet for scratching; the duck has webbed feet for swimming; birds like the sparrow† have feet adapted for holding on to thin branches; the heron† has long legs for standing in water (and a long beak for catching fish); the swift† has all its toes pointing forwards so that it can cling to a vertical surface; the woodpecker† has two toes pointing forwards and two pointing backwards, and with the aid of its stiff tail it can climb on vertical tree-trunks in search of

insects (see Fig. 108). (The woodpecker's beak is very sharp and is used for boring holes in bark: its tongue is also very long, with

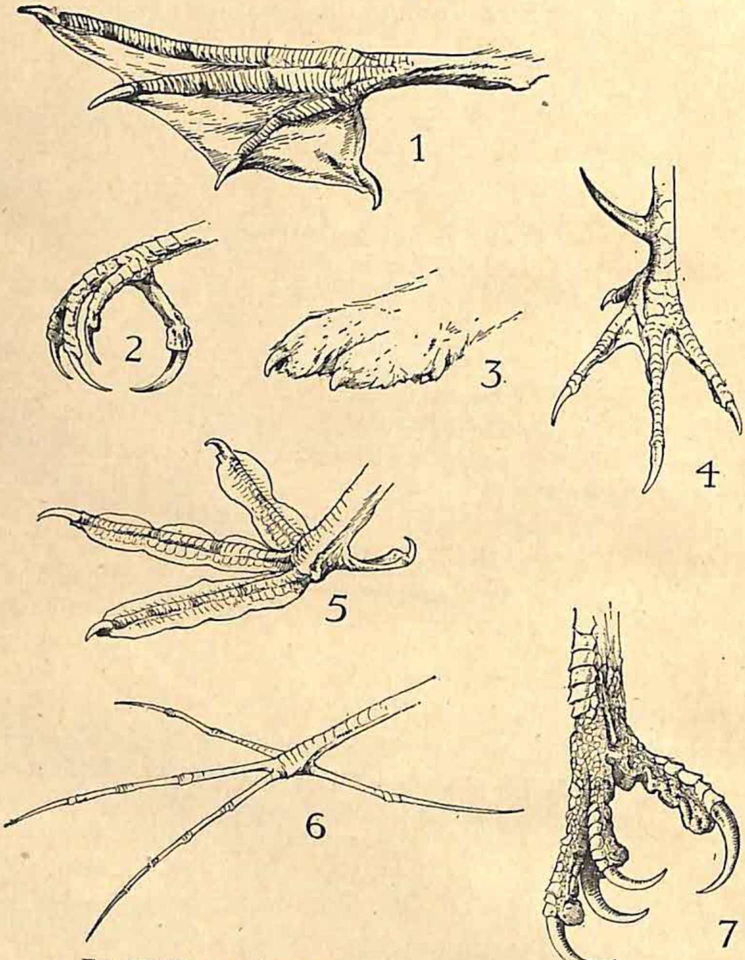


FIG. 108. Types of birds' feet adapted to different ways of life.

small hooks at the end, for dragging out insects from their holes.) Insect-catching birds (e.g. swift and night-jar†) have very wide

mouths guarded by stiff hairs that trap insects during flight. Owls have very soft feathers and therefore they fly very quietly at night. Their eyes are placed in front of the head (as in Man), hence owls can see clearly in a weak light. A few birds have lost the power of flight, but they have developed some other efficient type of movement: for example, an ostrich† has very strong legs and can run as fast as a horse; a penguin† is an excellent diver and swimmer.

THE SKELETON

(The following details of internal structure refer mainly to the pigeon.) The bones of birds are arranged on the same general plan as those of other vertebrates (see Fig. 109). Many of the bones,

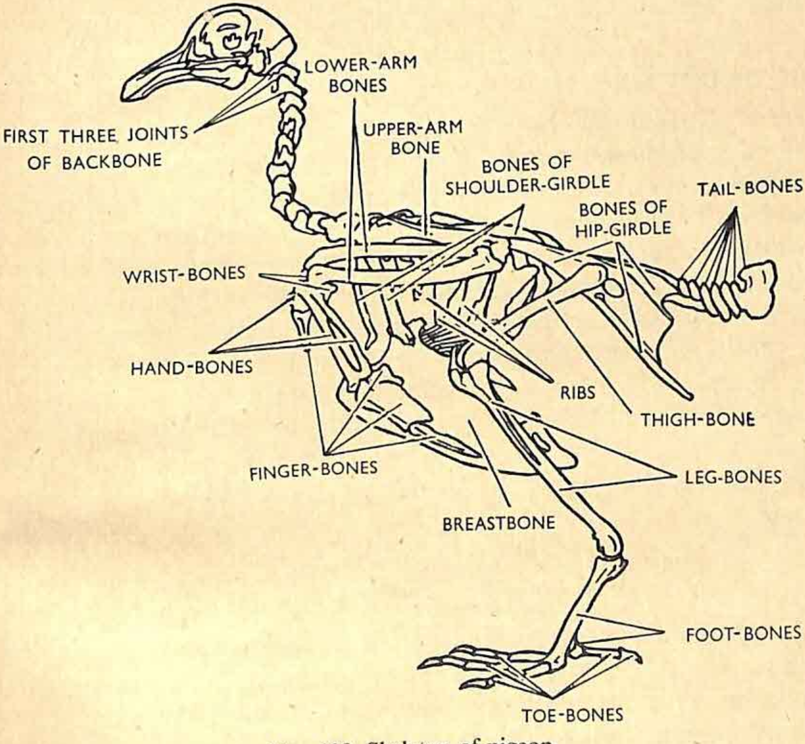


FIG. 109. Skeleton of pigeon.

however, contain air-spaces instead of marrow, so that they are very light. The breast-bone is very large and strong, with a projecting 'keel' to which the flying-muscles are attached. The shoulder-girdle and the hip-girdle are very strong in birds. There are the usual two pairs of vertebrate limbs, but the two fore-limbs are modified to form *wings*. At first sight, there appears to be little relation between the fore-limb of a frog and the wing of a bird, but an examination of the skeleton shows the same bones, the 'hand-bones' of the bird being partly joined together to form the wing.

The hind-limbs consist of thigh, leg, ankle, and foot, as in other vertebrates, but the ankle and foot are covered with *scales*, a fact which suggests that birds have evolved from reptiles.

THE DIGESTIVE SYSTEM

A bird has no teeth, so it cannot chew its food. Swallowing is helped by slimy saliva from the salivary glands, and the food passes down the gullet, which is usually enlarged to form a *crop* for storing the food before digestion. The food passes from the crop to the stomach, where it is mixed with a digestive juice before being passed on to the *gizzard*. This is a flattened sac with thick, muscular walls and a horny lining. With the help of small stones swallowed by the bird, the gizzard grinds up the food before it passes on to the long, coiled intestine for digestion and absorption (with the help of bile from the liver and pancreatic juice from the pancreas). The large intestine is very short and ends in a *cloaca*, an opening that also receives the ducts from the excretory and reproductive organs.

THE RESPIRATORY SYSTEM

When a bird breathes, the air passes down the long windpipe into the lungs. These are small spongy sacs that do not expand and contract during breathing like the lungs of other Vertebrates, but the air passes *through* the lungs into large *air-sacs* in the body-

cavity. (These air-sacs also lighten the body and so help in flying.) This half-used air in the air sacs is later forced out through the lungs again. In this way, a bird always has large reserves of air and can absorb oxygen when the air passes in through the lungs and also when it is forced out again. A bird's lungs and heart are exceptionally efficient.

REPRODUCTION IN BIRDS

Birds take a great deal of trouble to give their young a good start in life. The female bird lays hard-shelled eggs in which the young animal gradually develops with a supply of food and air. In most cases the eggs are laid in a carefully prepared nest that is hidden from enemies or built out of their reach. Birds use various devices to protect their eggs. The nest may be hidden in a mass of leaves, it may be placed high up in a tree or cliff, in a hole where it is difficult to get at, or it may be hung from very thin branches. The eggs are sometimes coloured so as to match their surroundings, especially when the nest is on the ground. A parent bird keeps the eggs warm for several weeks, until the young bird hatches out from the egg. In many cases the newly-hatched birds are helpless and unable to feed themselves, and the parents bring food to the nest until the young are completely covered with feathers and able to find their own food. But the young of some birds, e.g. fowls and ducks, are covered with down-feathers and are able to run about and feed themselves a few hours after they are hatched. Careful provision for their young, before and after hatching, is another factor that has helped to make birds one of the most successful groups of animals.

THE HIGHEST ANIMALS

The three great groups of vertebrate animals, the *mammals* on land, the *birds* in the air, and the *fishes* in water, are the most advanced of all the animals, and they have divided the world between them. Fishes, we have seen, have had a very long history,

and are a much older type than birds or mammals. There is reason to believe that birds and mammals have both evolved from reptiles, but along different lines, and they have both developed with great success to form two parallel classes of heat-retaining, high-efficiency animals.

CHAPTER IV

LIGHT

THE NATURE AND SPEED OF LIGHT

If a coil of resistance wire (e.g. nichrome) is gradually heated in a dark room by passing an electric current through it, first we *feel* that *heat* is being *radiated* from the hot wire. When the temperature of the wire reaches about 500° C., however, we begin to *see* the wire as it becomes red hot, i.e. it is now radiating both *light* and *radiant heat*. As the temperature becomes still higher, the light from the wire becomes stronger and brighter, until, at about 1,000° C., it appears white hot. When the hot wire gives out *light* in this way, we say that it is *luminous*. Radiant heat and light, therefore, are similar forms of energy, but radiant heat affects only the sensitive nerve-endings in our skin, while light affects the sensitive nerve-endings in our eyes.

In our studies of green plants we have noticed the relation between these different forms of energy. During *photo-synthesis*, *light energy* is converted into *chemical energy* stored up in carbohydrates, and during *respiration* some of this chemical energy is converted into *heat energy*. When plant products are burnt as fuels, their chemical energy is converted into heat energy, and we have seen how a heat engine converts this heat into *mechanical energy*. If a steam-engine drives a dynamo, mechanical energy is converted into *electrical energy*, which can be converted into light and heat once more in an electric light bulb. Light, therefore, is just another form of *energy*.

HOW LIGHT TRAVELS

When light reaches us from the Sun it has to pass through the atmosphere that surrounds the Earth, but during most of its

journey it passes through *empty space*, for, unlike sound, *light can travel through a vacuum*. One of the first things we notice about light is that (in a uniform medium [1]†) *it travels in straight lines*. The following experiments illustrate this:

(i) Arrange a motor-car headlamp bulb and a beaker of water so as to produce a parallel *beam* of light on a sheet of white paper on the bench as shown in Fig. 110 (*a*). Then place a narrow *slit* vertically in front of the beaker so as to get a very narrow parallel beam of light on the paper as shown in Fig. 110 (*b*). Test the beam for straightness.

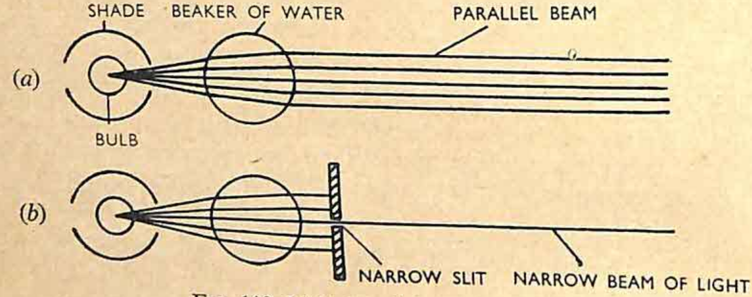


FIG. 110. Light travels in straight lines.

(ii) Take three pieces of cardboard, each pinned to a block of wood, and each with a small hole in the centre (all three holes being the same vertical height above the bench-top). Place the cards about six inches apart, one behind the other. Thread a piece of thin string through the holes in the three cards and then pull it tight so that the three holes are in the same straight line, as shown in Fig. 111. Now place a light behind the hole in the third card and put your eye in front of the hole in the first card. Notice that you can see the light through the holes, but if any one of the cards is moved

[1] The word '*medium*' is used here to mean 'anything through which light can pass'. We cannot use 'substance' or 'material' because light also passes through a *vacuum*. We are careful to say that 'light travels in straight lines *in a uniform medium*' because you will find later that when light passes obliquely from one medium into another, e.g. from air into glass, it is suddenly bent.

aside, so that the holes are no longer in line, then the light does not reach your eye.

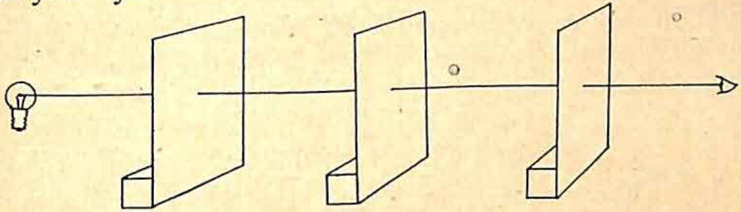


FIG. 111. Light travels in a straight line.

[TEACHERS' NOTE.—A cheap and effective 'ray apparatus' consists of a 12-volt 36-watt (or, even a 6-volt 24-watt) motor-car head lampbulb (run from a mains transformer) enclosed in a cylindrical shade (a '50' cigarette tin) which has two rectangular openings (1 in. wide and 1¼ in. high) cut from opposite sides at its open end (so that pupils can work on either side of the lamp). The shade is painted dead-black inside. A 600 c.cm. squat beaker, half-filled with water, serves as a cylindrical lens. The slits for single and triple rays are cut in carbon-paper gummed to a sheet of glass (e.g. an old photographic plate or a lantern-slide cover-glass—3¼ in. by 3¼ in.).]

SHADOWS

The formation of *shadows* depends on the fact that light travels in straight lines.

When the source of light is a small, bright point, e.g. an arc lamp or a motor-car headlamp bulb, a sharp, well-defined shadow is formed. Thus, as shown in Fig. 112 (*a*), when rays† of light from a luminous point A fall on a screen* S, if an opaque* ball B (i.e. one that will not allow light to pass through it) is held between the source of light and the screen, a well-marked, circular shadow is cast on the screen. Hang your motor-car headlamp bulb about six inches above a sheet of white paper on the bench. Take a wooden (or plasticine*) ball of about one inch diameter, and hold it on the end of a needle (or compass*-point) below the bulb, whose white-hot filament is practically a point of light. Notice that a circular, *complete shadow* is formed on the paper. Draw a diagram.

When the source of light is large, e.g. a large 'frosted' electric light bulb, besides the complete shadow we find also a half-shadow

or *partial shadow*, surrounding the complete shadow (see Fig. 112 (*b*)). Use a large, 'frosted' bulb in the same way as in your last experiment, varying the distance between bulb, ball, and paper. Notice that in certain positions *two* circular shadows are formed, a *complete shadow* in the middle, surrounded by a *partial shadow*. Draw a diagram.

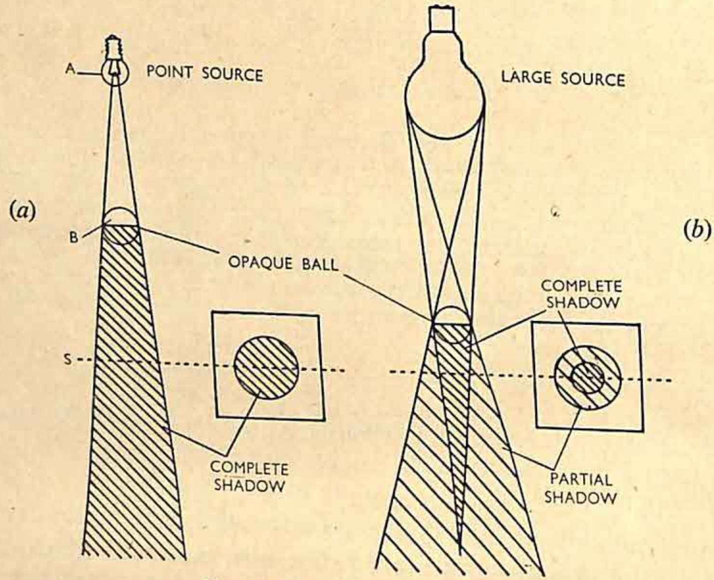


FIG. 112. Formation of shadows.

ECLIPSES

Eclipses† of the Sun and the Moon are due to shadows. When the Earth's shadow falls on the Moon, there is an eclipse of the Moon (by the Earth); and when the Moon's shadow falls on the Earth, there is an eclipse of the Sun (by the Moon).

In Fig. 113, S represents the *Sun*, E the *Earth*, and M the *Moon*. Since light travels in straight lines, the region ACF will be in *complete shadow*, and if the Moon is in this region it will be *totally eclipsed* (as shown in Fig. 113 (*a*)). The region ABC and

FCD is in *partial shadow*, and if the Moon is in this region there will be a *partial eclipse of the Moon*.

The Moon is much smaller than the Earth and casts a much smaller total shadow. Hence when the Moon is between the Earth and the Sun, only part of the Earth's surface will be in complete shadow at any one time, and on either side of this region of *total eclipse* will be regions from which part of the Sun is visible, and an observer on those parts of the Earth's surface will see a *partial eclipse of the Sun*. Fig. 113 (*b*) explains this.

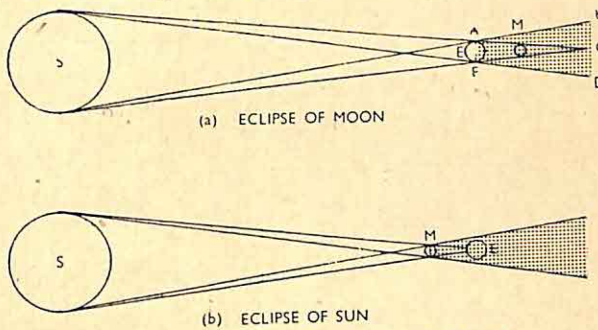


FIG. 113. Eclipses of the Sun and Moon.

THE SPEED OF LIGHT

When a gun is fired some distance away, the flash is *seen* before the explosion is *heard*. Similarly, when a thunderstorm is a mile away, the lightning is seen about five seconds before the thunder is heard, although the light and the sound were both caused by the same flash of lightning. This is because light travels very much faster then sound.

Before the eighteenth century it was thought that light did not require time to travel, but passed instantly, because all attempts to measure its speed had failed. About 1675, Römer, a Danish astronomer,* made the first estimate of the speed of light by observing the eclipses of one of the moons of the planet* Jupiter. Jupiter, which is the largest planet, takes about twelve years to revolve round the Sun, and has a number of moons revolving

round it, just as our own Moon revolves round our own planet, the Earth (see Fig. 114). One of these moons M_1, when viewed from the Earth, passes into Jupiter's shadow (i.e. it is eclipsed) at exactly regular intervals, once in every revolution round the planet. Römer observed the time at which the eclipse began when the Sun S, the Earth E_1, and Jupiter J were in the same straight line; and again, after 100 eclipses, six months later when the Earth E_2, the Sun S, and Jupiter J were again in line, as shown in Fig. 114. He

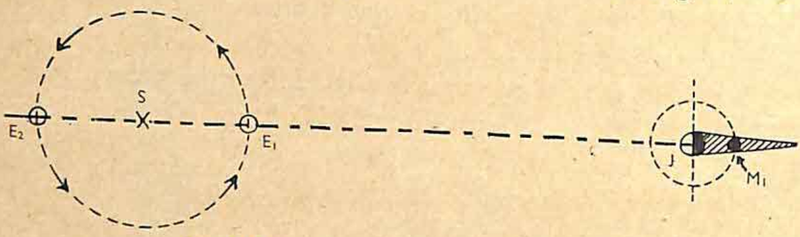


FIG. 114. Speed of light by Römer's method.

found that the eclipse took place 16 min. 36 sec. (= 996 sec.) *later than the calculated time* for 100 eclipses, and he concluded that the delay was due to the fact that the Earth is not always the same distance away from Jupiter, and that the difference of 996 seconds was the time taken for light to travel the distance E_1 E_2. This distance was known to be about 185,000,000 miles, hence the speed of light is $185{,}000{,}000 \div 996 = 186{,}000$ miles per second. This result agrees with more recent measurements by other methods.

Light travels with a speed of 186,000 miles per second (*or 300,000 kilometres per second*). (The speed of sound is about 1,150 *feet* per second.) Calculate how many times faster light travels than sound.

REFLECTION

When light falls on any object, three things may happen to it: (i) *the light may pass through the object*, i.e. *the light is transmitted*; (ii) *the light may be absorbed by the object*; (iii) *the light may be sent back from the surface*, i.e. *the light is reflected.*

Anything which transmits most of the light that falls on it, e.g. water or glass, is said to be *transparent*. Anything which does not transmit any of the light that falls on it is said to be *opaque*, e.g. wood and stone. Anything which transmits only part of the light that falls on it, e.g. 'frosted' glass, water containing a little suspended clay, is said to be *translucent*.

We shall now consider that part of the light which is *reflected*.

REGULAR AND SCATTERED REFLECTIONS

When a beam of light falls on a smooth, polished, flat surface, e.g. a sheet of glass or polished metal, or the surface of still water or mercury, it is reflected *regularly* as a *beam* of light (see

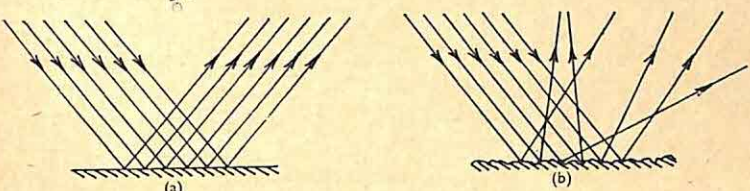


FIG. 115. Regular and irregular reflection.

Fig. 115 (*a*)). This type of reflection is called *regular reflection*, only the *direction* of the beam being changed.

(i) Set up your 'ray apparatus' (motor-car headlamp bulb, beaker of water, and narrow slit) to give a narrow parallel beam of light on a sheet of paper, and place a flat strip of mirror vertically in the path of the beam. Turn the mirror slowly, and notice that the character of the beam is unchanged after reflection, only its direction is changed. This experiment illustrates *regular reflection*.

(ii) When a beam of light falls on a rough surface, e.g. a sheet of white blotting-paper, no reflected beam is seen, but the light is *scattered* in all directions: that is, it is reflected *irregularly* (see Fig. 115 (*b*)). Repeat experiment (i), using a piece of unglazed paper instead of the mirror. Notice that the character of the beam is changed after reflection and that the light is scattered (or *diffused*) by the rough surface.

THE REFLECTION OF LIGHT AND THE FORMATION OF IMAGES BY FLAT MIRRORS

(i) Stand a thin, flat strip of mirror upright on a sheet of paper and stick a large pin upright at B, touching the front of the mirror (see Fig. 116). Stick another pin at A, about 2 in. in front of the mirror. Placing your eye just above the level of the paper, stick a third pin at C so that it *appears* to be in line with A and B. Draw a line XY to mark the front of the mirror, then remove the mirror and join AB and BC. The line AB marks the *incident*† *ray* and BC marks the *reflected ray*. Now draw BN perpendicular* to XY.

BN is called the *normal*† to the mirror at B. The angle ABN is the *angle of incidence* (*i*). The angle CBN is the *angle of reflection* (*r*). Measure these two angles *i* and *r* with your protractor.* They

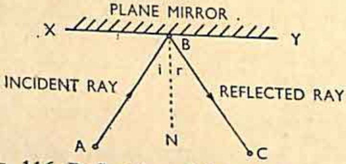


FIG. 116. Reflection of light by flat mirror.

are the same, i.e. *the angle of incidence is equal to the angle of reflection*. This is the *Second Law of Reflection*.

(ii) Stand a flat mirror strip in an upright position on a sheet of paper and stick a large pin upright at A, about 2 in. in front of the mirror. Draw the line XY to mark the reflecting (silvered) surface of the mirror, as shown in Fig. 117. Placing your eye just above the level of the paper, observe the position of the image* of the pin in the mirror, and stick two more pins at B and C so that these two pins are in line with the image of A in the mirror. Mark the pin-holes B and C. Observe from another angle the position of the image of the pin A in the mirror, and stick two more pins at D and E so that they are in line with the image of A. Now remove the mirror and pins and join BC and DE. Then produce* these lines behind the reflecting surface XY. The lines meet at a point A_1, which marks the position of the image of A in the mirror. *Join* AA_1,

and notice that this line is perpendicular (*or normal*) *to the reflecting surface XY, and also that A_1 is just as far behind the mirror as A is in front of it, i.e. $AO = OA_1$.*

(iii) Draw JK normal to the surface at K, where BA_1 cuts XY. Join AK. It is clear that the light has actually travelled from A to B along AKB.

AK is called the incident ray and KB is the reflected ray. The angle

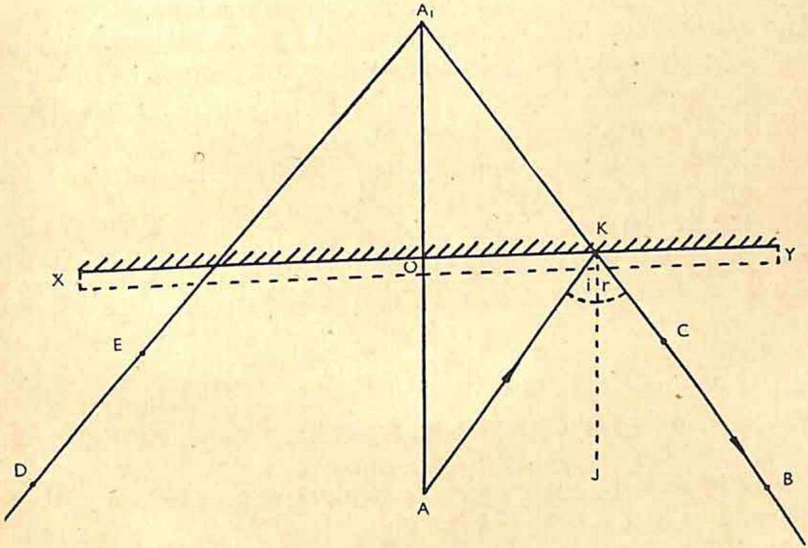


FIG. 117. Reflection of light by flat mirror.

AKJ (*i*) *is called the angle of incidence, and the angle BKJ* (*r*) *is the angle of reflection*. Measure these angles.[1] It is found that *the angle of incidence is equal to the angle of reflection.*

(In Fig. 117, in which the mirror is shown in section, AO is *perpendicular* to the line XY. In your actual experiment, however, the mirror is a *plane** (flat surface) and not merely a line, and AO

[1] At first sight, it would seem easier to measure the angle between the light-ray and the mirror. You will understand the reason for measuring the angle between the light ray and the *normal* when you come to study curved mirrors.

is perpendicular to any line lying in this plane which passes through O. That is, AO is *perpendicular to the surface*, or *normal to the surface*.)

Verify this with your 'ray apparatus'. Arrange it as shown in Fig. 110 (*b*), so as to give a narrow parallel beam of light on a sheet of paper lying on the bench, and place a strip of plane mirror obliquely in the path of the ray. Mark in pencil: (*a*) the reflecting surface of the mirror, (*b*) the incident ray, and (*c*) the reflected ray. Remove the mirror and draw, with a set-square, the normal to the mirror at the point of incidence. Measure the angle of incidence and the angle of reflection.

What do you find? ....

Replace the mirror so that it makes a different angle with the ray, and repeat the experiment.

What do you find? ....

Compare the angles of incidence and the angles of reflection in your two experiments, and notice that *if the mirror is turned through any given angle, the reflected ray is turned through twice that angle.*

THE LAWS OF REFLECTION OF LIGHT

First Law:—*The incident ray, the reflected ray, and the normal to the reflecting surface at the point of incidence all lie in the same plane* (so we can draw them on a sheet of paper).

Second Law:—*The angle of incidence is equal to the angle of reflection.*

It can be shown *geometrically*, from these two laws, that, *for a flat mirror*, the position of the image of a point in front of the mirror is found by drawing the perpendicular from the point to the mirror and then producing it for an equal distance behind the mirror. You have already shown this *experimentally* in (ii) above (see Fig. 117).

THE SIMPLE PERISCOPE

The simple periscope† applies the laws of reflection. Set up two plane mirrors as shown in Fig. 118, each making an angle of 45°

with the horizontal. This arrangement forms a simple periscope that can be used for obtaining a clear view over a wall or bank.

Use your 'ray apparatus' to show the principle of the simple periscope, arranging it to give a narrow parallel beam, and placing two strips of plane mirror in suitable positions as shown in Fig. 119.

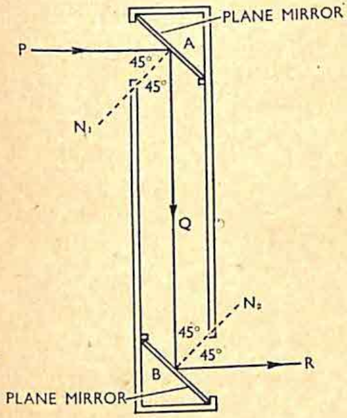


FIG. 118. Simple periscope.

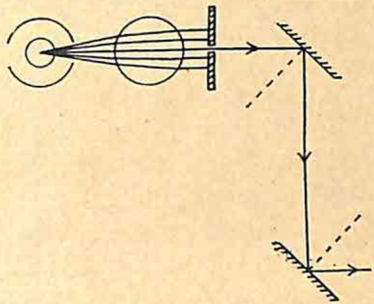


FIG. 119. Principle of periscope.

HOW TO FIND THE POSITION OF IMAGES IN PLANE MIRRORS BY GEOMETRICAL CONSTRUCTION

We know that the image of an object is on the normal to the reflecting surface, and as far behind the mirror as the object is in front of it. It is therefore a simple matter to find the position of such images by drawing.

(i) In Fig. 120, AB is an object lying in front of the mirror XY. The point A will form an image *a* lying on the normal to the mirror through A and as far behind the mirror as A is in front. Similarly the point B will form an image *b*, hence *ab* is the image of AB. Fig. 120 also shows the path by which the actual rays of light travel from the object AB to reach the eye at E.

(ii) In Fig. 121, A is an object between two mirrors OX and OY, inclined at right-angles to each other. The object A will form one

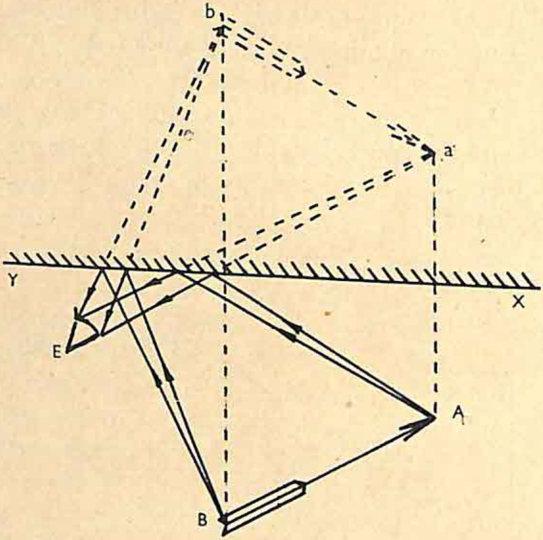


FIG. 120. Formation of image by plane mirror.

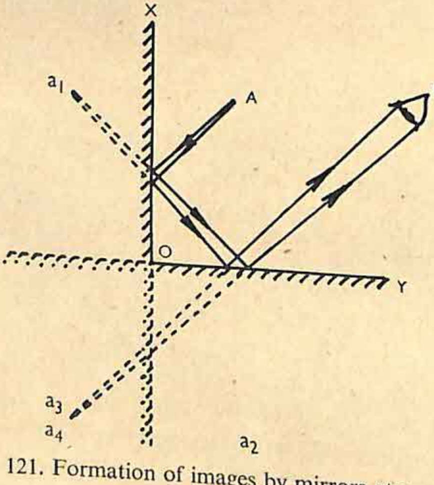


FIG. 121. Formation of images by mirrors at an angle.

image a_1 behind OX and another image a_2 behind OY. The image a_1 is still in front of the mirror OY, produced, and will, therefore, form another image at a_3. In the same way, the image a_2 is still in front of the mirror OX, produced, and will form another image at a_4. It is clear from the figure, however, that a_3 and a_4 will coincide,* so that only *three* images are seen. Fig. 121 also shows how rays from A reach the eye at E after two reflections.

(iii) In Fig. 122, O is an object between two parallel mirrors AB and CD. The object O will form an image I_1 behind AB. But this

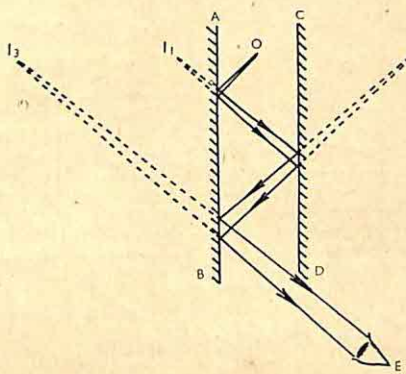


FIG. 122. Formation of images by parallel mirrors.

image I_1 is still in front of the mirror CD and will, therefore, produce another image I_2 behind CD. This image I_2 will form another image behind AB at I_3, and so on.

How many images will be formed altogether? . . . .

Try this with two parallel mirrors. Fig. 122 shows how rays from the third of these images (I_3) reach your eye.

CURVED MIRRORS

The simplest curved mirrors are *spherical*, i.e. the reflecting surface forms part of the surface of a *sphere*. The radius of the sphere is also the *radius of curvature* of the mirror, and the centre of the sphere is called the *centre of curvature* of the mirror. The middle

point of the reflecting surface is called the *pole*† of the mirror, and the line joining the pole to the centre of curvature is called the *axis* of the mirror.

If the mirror has its reflecting surface on its hollow side it is said to be a *concave mirror*. Headlamp reflectors are usually of this type. If the mirror has its reflecting surface on the outside of the curved surface it is a *convex mirror*, e.g. the mirrors fitted to motor-lorries to enable the driver to see behind him. The law that the angle of incidence is equal to the angle of reflection applies also to curved mirrors.

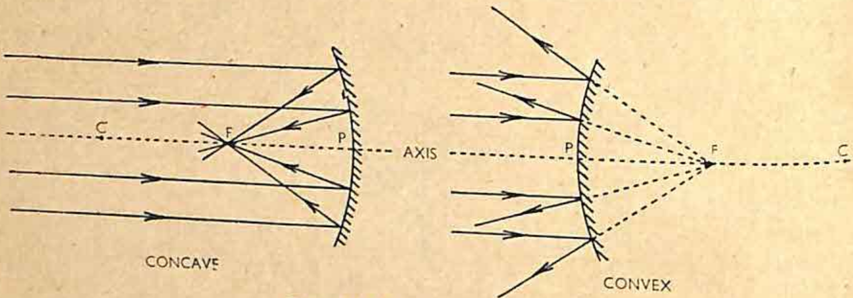


FIG. 123. Spherical mirrors.

THE FOCUS OF A SPHERICAL MIRROR

The Sun is so far away from us that its rays can be considered to be parallel. If parallel rays from the Sun or any other distant object are allowed to fall on a *concave* mirror they appear to *converge* at a point F half-way between the pole of the mirror P and the centre of curvature C, as shown in Fig. 123. This point is called the *focus*† of the mirror.

If parallel rays are allowed to fall on a *convex* mirror, they appear to *diverge** from a point F behind the mirror, as shown in Fig. 123.

The focus of a curved mirror is the point through which parallel rays falling on the mirror are reflected, or from which they appear to have been reflected. It lies half-way between the pole of the mirror and the centre of curvature.

The distance of the focus from the mirror is called the focal length† *of the mirror, and in the case of a spherical mirror the focal length is half the radius of curvature.*

HOW TO FIND THE FOCAL LENGTH OF A SPHERICAL MIRROR

(i) Hold a small piece of white cardboard in front of a *concave* mirror as shown in Fig. 124, so that parallel rays from the Sun or some other distant object are reflected from the mirror on to the cardboard. Move the cardboard backwards and forwards until it receives a clear image of the distant object. Measure the distance between the screen and the pole of the mirror. This is the focal

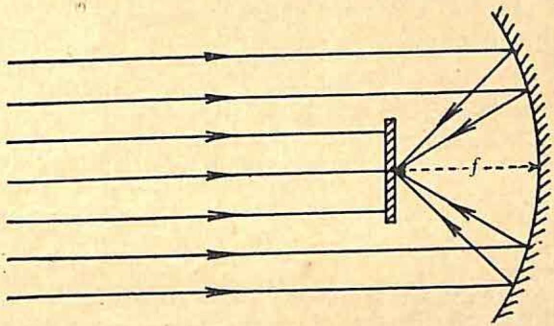


FIG. 124. Finding the focal length of a concave mirror.

length (f) of the mirror. (If you use the Sun as your distant object, notice that the radiant heat is also reflected to the same focus as the light rays. Focus an image of the Sun on the back of your hand!)

(ii) Arrange your 'ray apparatus' so as to throw a broad parallel beam of light on a sheet of paper; then place in front of the beaker a screen with three vertical slits so as to throw three narrow parallel beams of light on the paper. Place a strip of cylindrical *concave* mirror in the path of the rays, as shown in Fig. 125, and notice how the reflected rays *converge* to pass through the focus. Mark this point on your paper, also mark the reflecting surface of your curved

mirror, then remove the mirror and measure (*a*) the focal length ...., (*b*) the radius of curvature of the mirror ....

What is the relation between (*a*) and (*b*)? ....

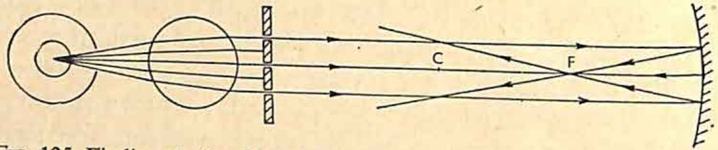


FIG. 125. Finding the focal length of a concave mirror with the ray apparatus.

In Fig. 125, F is called a *real focus*† because the rays of light *really* pass through this point.

(iii) Repeat your last experiment, using a strip of cylindrical *convex* mirror instead of the concave mirror, as shown in Fig. 126. Notice that the parallel rays *diverge* after reflection. Mark the reflected rays on your paper, and also the reflecting surface of the mirror. Remove the mirror and produce the three reflected rays

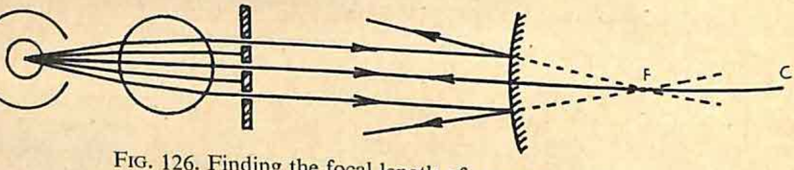


FIG. 126. Finding the focal length of a concave mirror.

backwards until they meet behind the mirror. Measure (*a*) the focal length.............., (*b*) the radius of curvature.............

In Fig. 126, F is a *virtual* focus*† because the rays of light only *appear* to come from F. In the same way, the images formed by plane mirrors are always *virtual images*.†

GEOMETRICAL CONSTRUCTION OF IMAGES IN SPHERICAL MIRRORS*

We can easily find, by geometrical construction, the position of the image formed by an object in a curved mirror. Among the

millions of rays that fall on the mirror there are *three* that are useful in our construction:

(i) *Any ray that passes through the centre of curvature will fall normally on the mirror and will be reflected back along its own path.*[1]

(ii) *Any ray parallel to the axis is reflected back through the focus.*

(iii) *Any ray passing through the focus is reflected back parallel to the axis.*

These three rays are shown in Fig. 127, and if we draw any two

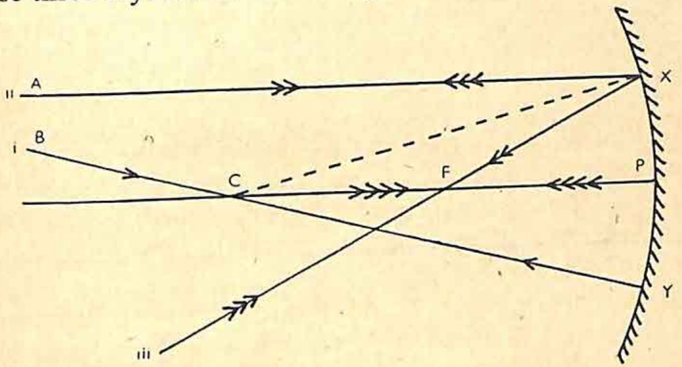


FIG. 127. Rays used in geometrical construction of images.

of these reflected rays, their point of intersection* gives the image of the point in the mirror.

HOW TO FIND THE POSITION OF IMAGES IN SPHERICAL MIRRORS

(i) In Fig. 128, P is the pole of the mirror, F is the focus, C is the centre of curvature, and AB is an object placed *on the farther side of C from the mirror*. To find the position of the image of AB, AD

[1] You will now understand why we measure our angles from the *normal* and not from the surface of the mirror. The normal to a spherical mirror is simply a radius of the sphere. A spherical mirror can be regarded as being made up of a very large number of tiny plane mirrors, each lying along a *tangent** to the surface. In Fig. 127, the tangents at X and Y represent the parts of the mirror that reflect the rays AX and BY. In geometry lessons we have learnt that the radius of a circle is perpendicular to the tangent, hence CX is the normal to the mirror at X and BY is the normal to the mirror at Y. By the Second Law of Reflection, the angle AXC = the angle FXC.

is drawn through A parallel to the axis. A ray of light along AD will be reflected through the focus F along DF, produced. Hence the image of A lies somewhere along DF, or DF produced. AC is drawn through A and the centre of curvature C. A ray of light travelling along AC strikes the mirror normally and will be reflected back along the same path, hence the image of A lies somewhere along AC, or AC, produced, i.e. the image of A lies at the point of intersection of AC and DF produced. The image of B will lie somewhere along the axis, hence *ab* is the image of AB.

Verify* this on the optical* bench [1] with a *concave* mirror of known focal length.

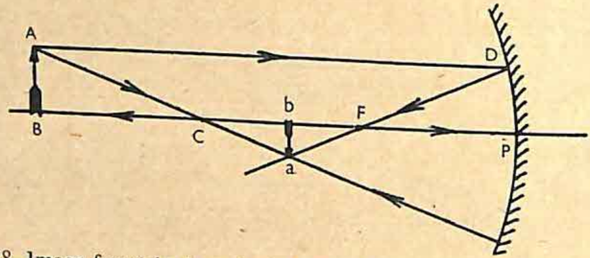


FIG. 128. Image formed when the object is beyond the centre of curvature.

(ii) Taking another position of the object AB *between the focus and the centre of curvature*, we can find the position of the image *ab* by using exactly the same construction, as shown in Fig. 129.

Verify this with a *concave* mirror of known focal length on the optical bench.

(iii) When the object AB is *between the focus and the mirror*, we can find the position of the image *ab* by the same construction, as shown in Fig. 130.

Verify this on the optical bench with a *concave* mirror of known focal length.

(iv) The position and size of the images formed in *convex* mirrors

[1] A cheap and effective 'home-made' optical bench is described in G. N. Pingriff's *Practical Physics* (Bell), p. 165.

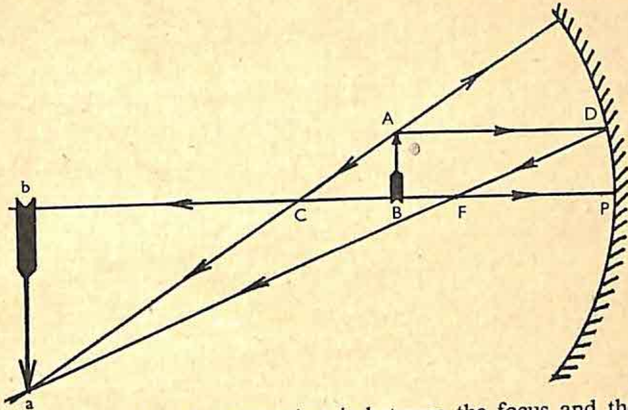


FIG. 129. Image formed when the object is between the focus and the centre of curvature.

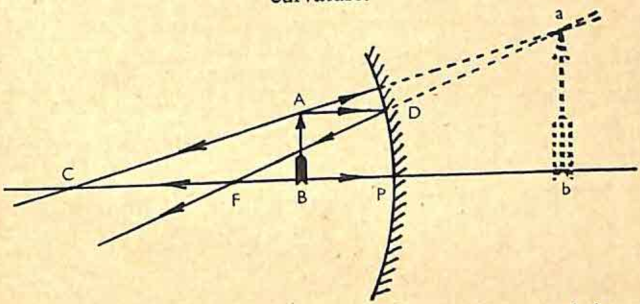


FIG. 130. Image formed when the object is between the focus and the mirror.

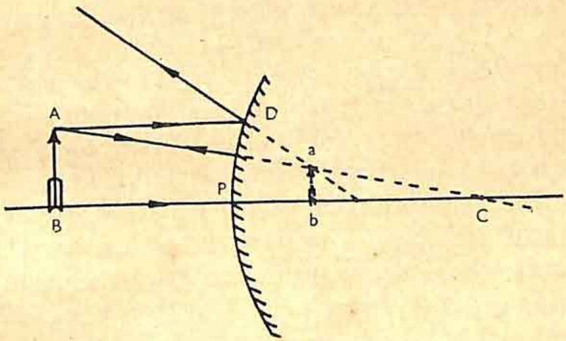


FIG. 131. Image formed by convex mirror.

can be found in just the same way, by geometrical construction, as shown in Fig. 131.

Verify this on the optical bench with a *convex* mirror.

In (i) and (ii) the rays of light really pass through the image, and the image can be caught on a screen.

What kind of image is this? ....

In (iii) and (iv) the rays of light do not really pass behind the mirror, but only appear to do so, and the image cannot be caught on a screen.

What kind of image is this? ....

In (i) *when the object is farther from the concave mirror than the centre of curvature*, the image is *real*, *diminished* in size, and *inverted*.

In (ii) *when the object is between the centre of curvature and the focus of a concave mirror*, the image is *real*, *magnified* in size, and *inverted*.

In (iii) *when the object is between the focus and the concave mirror*, the image is *virtual*, *magnified*, and *upright*.

In (iv) *when the object is anywhere in front of a convex mirror*, the image is always *virtual*, *diminished*, and *upright*.

Notice that there are *three* different types of image with *concave* mirrors, but only *one* type with *convex* mirrors.

REFRACTION

Light travels *in air* with a speed of 186,000 miles per second but through a denser medium its speed is slower. Thus in water its speed is about 25 per cent. slower; in glass it is about 33 per cent. slower; while in diamond it is about 60 per cent. slower. In a vacuum, light travels at about 186,300 miles per second.

As a result of this difference in the speed of light through different transparent media, there is *refraction*†, or *change of direction*, when light passes obliquely from one transparent medium into another (although *in a uniform medium* light always travels in straight lines).

The following simple experiment will help you to understand what happens to light when it passes from one medium into another.

Spread a two-inch strip of fine sand on a smooth bench-top. Then roll an empty cotton-reel* across the bench in a direction *at right angles* to the sandy strip. Notice that although the sand slows down the reel it does not alter its direction (see Fig. 132). Now roll the reel across the bench so that it meets the edge of the sand *obliquely*. Notice that the reel changes direction (swinging towards

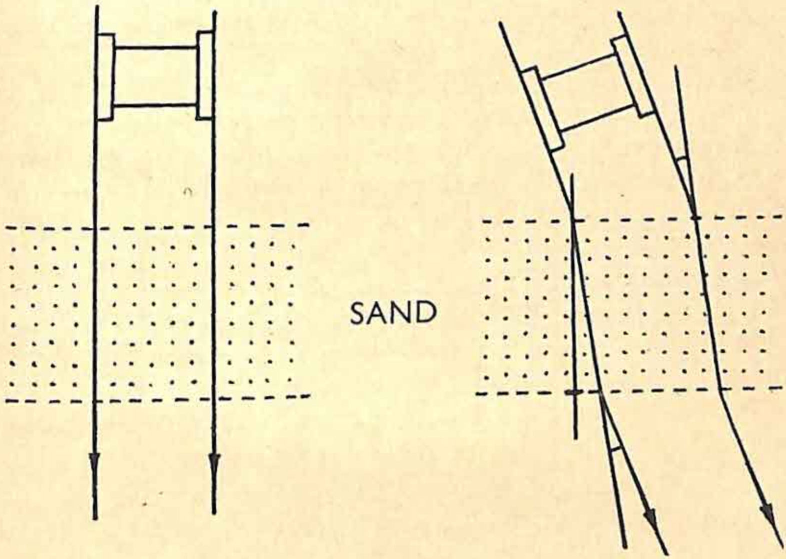


FIG. 132. Experiment illustrating the principle of refraction.

the normal on reaching the sand) and that as it passes from the rough surface to the smooth it tends to regain its original direction.

A similar change of direction takes place whenever light travels obliquely from one medium into another medium in which its speed is different. *When light travels obliquely from one medium into another in which its speed is less, its direction is changed towards the normal.* Conversely, when light travels obliquely from one medium into another in which its speed is *greater*, its direction is changed *away from the normal*.

This change of direction that takes place when light passes obliquely from one transparent medium into another is called *refraction*, and the light is said to have been *refracted*.

EXPERIMENTS ON REFRACTION

(i) Arrange your 'ray apparatus' so as to give a very narrow beam of light (see Fig. 133). Take a rectangular block of glass,

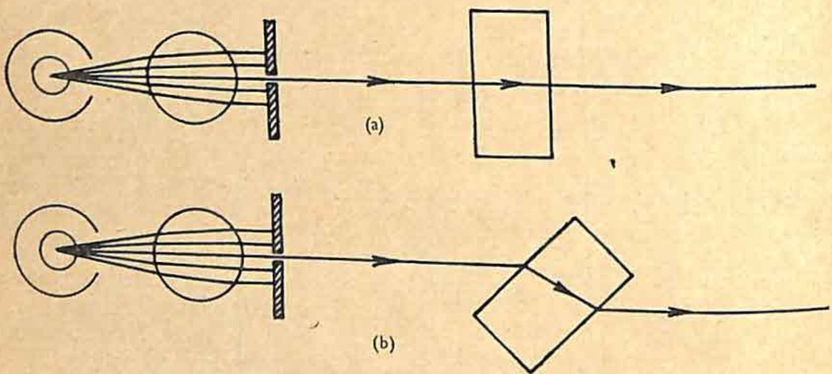


FIG. 133. Refraction of light by rectangular glass block.

roughened [1] on one of its larger faces, and place it with the rough side downwards in the path of the beam. Notice (*a*) that when the incident ray enters the glass *normally* (see Fig. 133 (*a*)) there is *no change in direction* as the beam passes through the glass and emerges on the other side; (*b*) that when the beam does not strike the glass at right angles (see Fig. 133 (*b*)) there is a change in direction, the ray being bent *towards the normal*, and that as the ray emerges on the other side of the glass block there is a further change in direction, so that *the emergent ray is parallel to the incident ray*.

[1] For use with the 'ray apparatus', glass blocks and prisms can be roughened on one side by rubbing on emery-paper wetted with turpentine; or, better, by grinding on a piece of plate-glass with carborundum powder wetted with freshly-distilled pine turpentine in which camphor has been dissolved.

(ii) Place a rectangular block of glass on a sheet of paper, and mark its outline in pencil, as shown in Fig. 134. Stick two large pins at A and B on the far side of the block. Look at these two pins *through the glass block*, and stick two more pins at C and D so that they appear to be in a straight line with A and B. Remove the glass block. Join AB and produce to meet the face of the block at X.

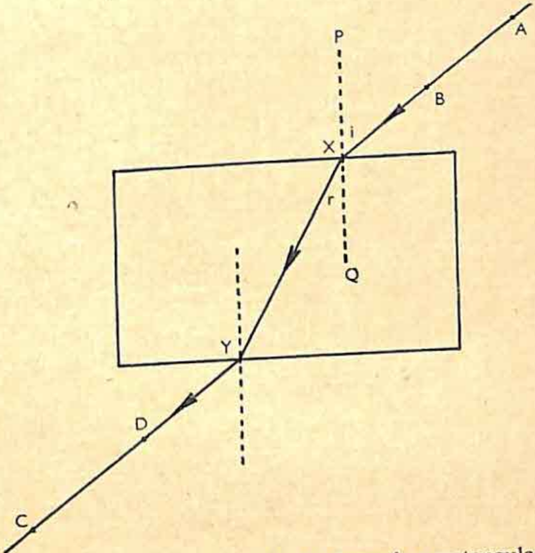


FIG. 134. Tracing the path of a ray of light through a rectangular glass block.

Join CD and produce to meet the other face of the block at Y. Join XY. Draw PXQ, the normal at X.

In Fig. 134, the line ABX represents a beam of light travelling through air and entering the glass block obliquely. As it leaves the air and enters the glass at X its speed becomes less and it is refracted towards the normal. XY represents the path of the refracted ray through the glass. The angle AXP is the *angle of incidence*, while the angle YXQ is the *angle of refraction*. As the beam emerges from the glass at Y and re-enters the air, its speed increases again and it is refracted away from the normal, along YDC.

Notice that since the sides of the block are parallel the emergent ray YDC also is parallel to the incident ray ABX, i.e. its final direction is the same although it has been displaced sideways.

SOME EVERYDAY EFFECTS OF REFRACTION

(i) Place a coin on the bottom of an empty vessel, e.g. a cigarette tin, and place your eye in such a position that the coin is just hidden by the side of the vessel. Keep your eye in this position while you pour water into the vessel. The coin comes into sight, and appears to rise as the water rises. Fig. 135 explains this. The light from the

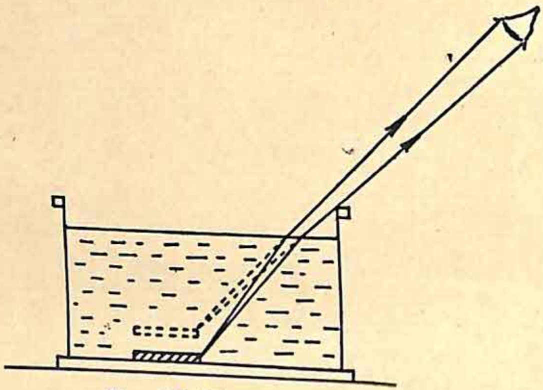


FIG. 135. Viewing a coin in water.

coin is refracted downwards on leaving the water and thus enters your eye; but to your eye *it appears* that the coin has been raised because you are so used to the idea that light travels in straight lines.

(ii) Put a wooden ruler obliquely into water and look down at it from one side. It appears to be bent at the surface of the water. (Fig. 136 explains this.) This is due to the refraction of rays of light when passing from water into air, but your brain assumes that the light has travelled in straight lines.

For the same reason, a swimming-pool always appears shallower than it really is.

THE INDEX OF REFRACTION (REFRACTIVE INDEX)

We have seen that the speed of light varies in different materials and thus causes refraction. The extent to which a material bends light in this way is usually expressed numerically by the *refractive index*† of the substance. It can be shown, theoretically, that *the*

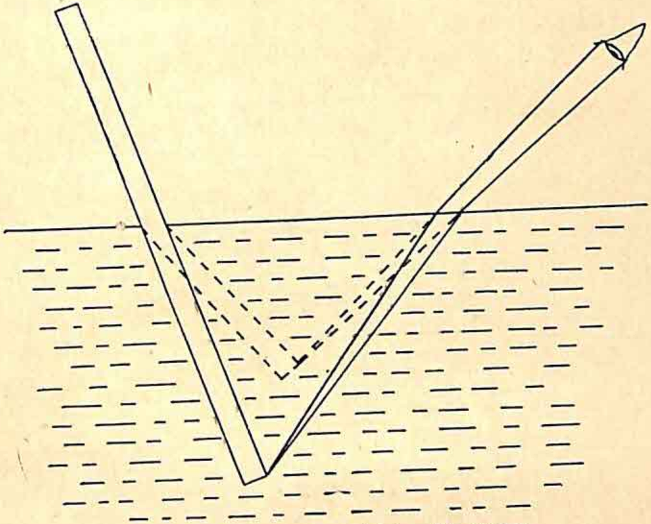


FIG. 136. Viewing a straight rod in water.

refractive index of a transparent material is the ratio of the speed of light in air [1] *to its speed in the material*, e.g.

$$\text{REFRACTIVE INDEX OF WATER} = \frac{\text{SPEED OF LIGHT IN AIR}}{\text{SPEED OF LIGHT IN WATER}} = \frac{4}{3}$$

In practice, it is not necessary to find these speeds directly, since it can be shown that

$$\frac{\text{SPEED IN AIR}}{\text{SPEED IN WATER}} = \frac{\text{REAL DEPTH}}{\text{APPARENT DEPTH}}$$

and these two quantities are easily found.

[1] More strictly, in a vacuum.

HOW TO FIND THE REFRACTIVE INDEX OF GLASS

Place a rectangular glass block on a sheet of paper and mark its front edge with a pencil line. Stick a pin A against its back face, then stick two more pins at C and D, so that C and D appear to be in line with A seen through the glass, as shown in Fig. 137. Mark these positions. Stick two more pins at E and F, so that E and F appear to be in line with A seen through the block. Remove the

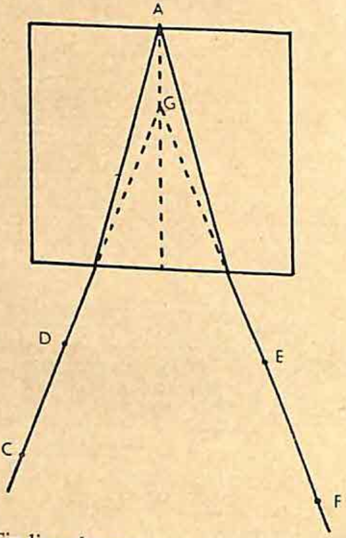


FIG. 137. Finding the apparent thickness of a glass block.

glass block. Join CD and produce. Then join EF and produce to cut CD produced at G. Then G is the *apparent* position of A when viewed through the glass block. The perpendicular distance from A to the front face of the glass block is the *real thickness*, and the perpendicular distance from G to the front face is the *apparent thickness*.

Therefore,

$$\text{REFRACTIVE INDEX OF GLASS} = \frac{\text{REAL THICKNESS}}{\text{APPARENT THICKNESS}} = \frac{\quad}{\quad} = \ldots\ldots\ldots$$

HOW TO FIND THE PATH OF THE REFRACTED RAY BY GEOMETRICAL CONSTRUCTION

If we know the *refractive index* of a transparent medium, we can easily trace the path of a beam of light from air into the medium, or vice versa, by geometrical construction. Suppose we want to follow the course of a ray AO that strikes the surface of some water at an angle of 45° as shown in Fig. 138. (The refractive index

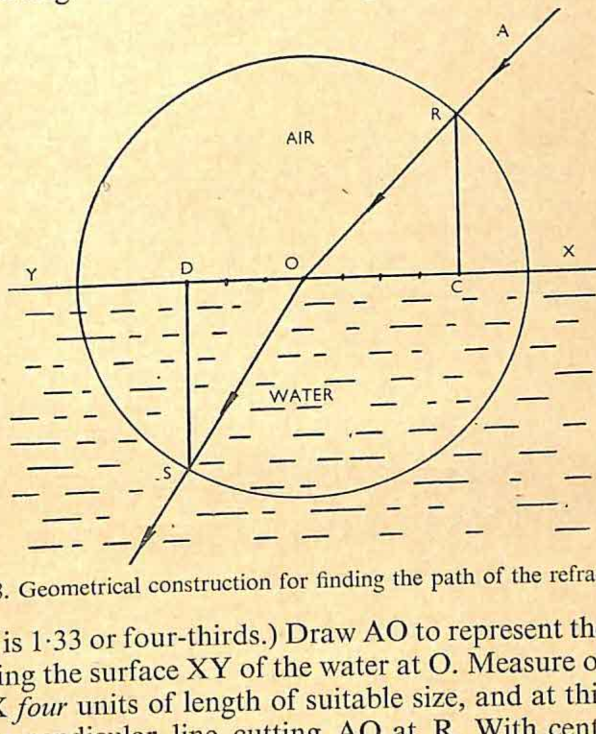


FIG. 138. Geometrical construction for finding the path of the refracted ray.

for water is 1·33 or four-thirds.) Draw AO to represent the incident ray, striking the surface XY of the water at O. Measure off from O along OX *four* units of length of suitable size, and at this point C draw a perpendicular line cutting AO at R. With centre O and radius = OR, draw a circle. Measure off from O along OY *three* units of length (i.e. OC ÷ the refractive index of water), and at this point D draw a perpendicular DS cutting the circle at S. Join OS; then OS marks the path of the refracted ray. (N.B.—The use of squared paper makes this construction very simple.)

HOW TO FIND THE REFRACTIVE INDEX OF GLASS USING A SEMICIRCULAR GLASS BLOCK

The same principle can be used with your 'ray apparatus' and a semicircular* glass block, roughened on one semicircular face, as shown in Fig. 139. A vertical line is drawn (with a diamond) down the centre of the rectangular edge of the block. Notice that any ray in the plane of the paper entering the block at O will always strike the curved surface normally and pass out of the glass without further bending. Mark on your sheet of paper (*a*) the outline of the

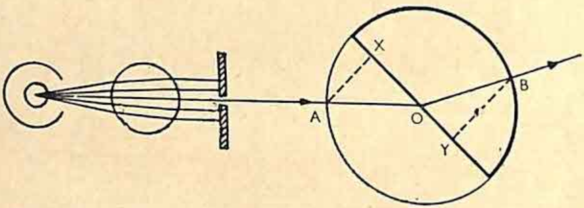


FIG. 139. Using a semicircular glass block to find the refractive index of glass.

glass block, (*b*) the direction of the incident ray AO, (*c*) the direction of the refracted ray OB. Remove the glass block, then complete the circle and the path of the refracted ray. Draw the perpendiculars AX and BY and measure OX and OY.

The refractive index of glass $= \dfrac{OX}{OY} = \dfrac{\qquad}{\qquad} = \ldots\ldots\ldots$

If you have done any *trigonometry*,* you will have noticed that

$$\frac{OX}{OY} = \frac{\text{the } sine^* \text{ of the } angle\ of\ incidence}{\text{the } sine \text{ of the } angle\ of\ refraction}$$

No matter how much the angle of incidence changes, this ratio $\dfrac{\sin i}{\sin r}$ always has a constant value (called the *refractive index* of the transparent material used, and usually represented by the Greek letter "mu", which is written μ). This constant relationship between *sin i* and *sin r* is called *Snell's Law* (after its discoverer). It is also known as the *Second Law of Refraction*. The *First Law of*

Refraction will remind you of the First Law of *Reflection*, for it states that *the incident ray, the refracted ray, and the normal to the surface of separation between the two media at the point of incidence all lie in the same plane.*

TOTAL INTERNAL REFLECTION

When rays of light travel obliquely from a dense medium like glass or water into a less dense medium like air, they are always bent *away from the normal* as shown in Fig. 140. If a beam of light OA is thrown vertically upwards through some water, its angle of

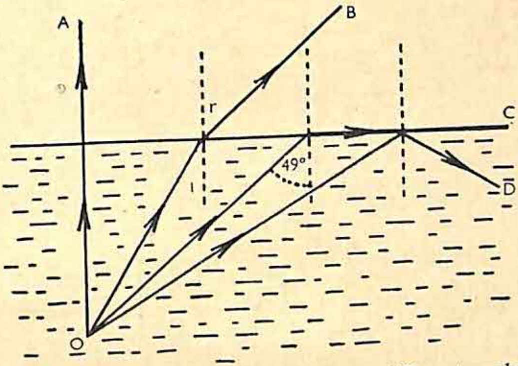


FIG. 140. Rays emerging from water at different angles.

incidence is 0°, i.e. it is normal to the surface and passes on into the air without refraction.

If the angle of incidence (i) is gradually increased, as in the ray OB, the angle of refraction (r) also increases, but more rapidly than the angle of incidence. When the *angle of refraction* is 90°, as in the ray OC, the refracted ray will just pass along the surface of the water. If the angle of incidence is increased beyond this, as in the ray OD, *the refracted ray will not emerge at all, but will be totally reflected back into the water. The angle of incidence at which the refracted ray disappears is called the critical* angle.*†

For water, this *critical angle* is 49°, for glass it is 42°, and for diamond, the densest transparent medium, it is 24°.

(i) As shown in Fig. 141, to an eye at E (e.g. a fish's) below the surface of a calm pool of water, all objects above the water-level appear to be crowded together within a cone. Outside this cone

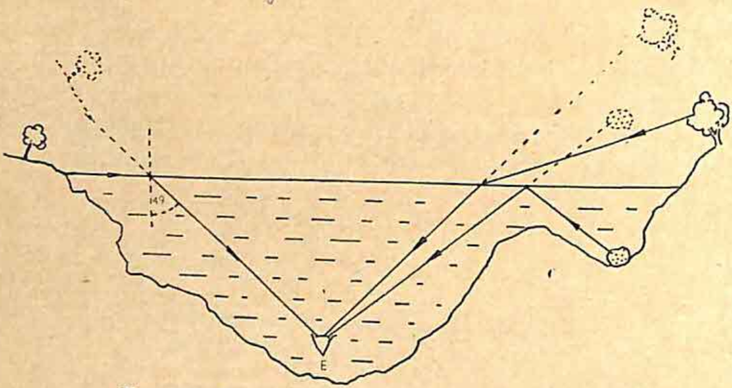


FIG. 141. Rays entering an eye beneath still water.

will be seen, by total internal reflection, objects lying some distance away on the bottom of the pool.

(ii) A right-angled glass prism is often used in optical instruments

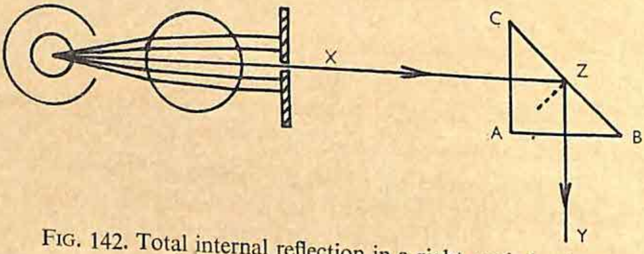


FIG. 142. Total internal reflection in a right-angled prism.

instead of a mirror, e.g. in periscopes, prismatic field-glasses, rangefinders, prismatic compasses, and camera view-finders. As shown in Fig. 142, if a ray of light X enters normally through the face AC it will pass straight on until it reaches the hypotenuse* BC at Z, making an angle of incidence of 45°. But this angle is greater

than the critical angle for glass (42°), hence the ray is totally reflected along ZY, emerging at right-angles to its original direction. Verify this with your 'ray apparatus' and a right-angled glass prism with one of its triangular faces roughened.

(iii) A right-angled prism can also be used to turn a ray of light through 180°, as shown in Fig. 143, when the incident ray enters normally through the hypotenuse face of the prism. The angle of incidence on the inner face of the prism is 45°, and as this is greater than the critical angle for glass (42°) there is a double internal reflection. Verify this with your 'ray apparatus' as in (ii) above.

(iv) The critical angle of diamond is very small (24°), hence a

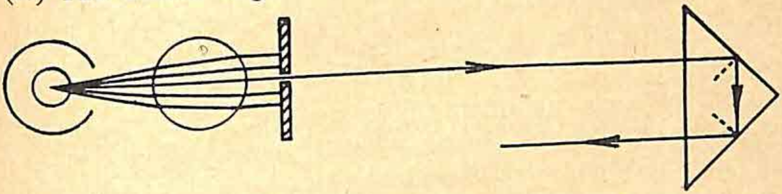


FIG. 143. Double internal reflection in a right-angled prism.

great deal of the light that enters a diamond is totally reflected and its inner surface appears very bright.

THE REFRACTION OF LIGHT BY PRISMS

We have studied the refraction of light as it passes through blocks of glass with parallel sides, and we have found that a ray of light emerges parallel to its original direction.

If a ray of light passes through a glass block whose faces are not parallel, e.g. a triangular prism, the ray will not usually emerge parallel to its original direction after passing through the prism.

(i) Place a glass triangular prism XYZ on a sheet of paper and mark its faces on the paper in pencil. Place two pins A and B opposite one face of the prism in positions like those shown in Fig. 144. Then look at these pins A and B *through the prism* and stick in two more pins C and D so that all four pins appear to be in one straight line. Remove the prism. Join AB and produce to meet the

face XY at R. Also join CD and produce to meet the face XZ at S. Join RS. Then the line RS represents the path of the ray of light inside the prism.

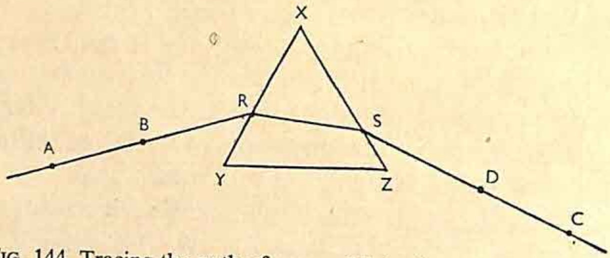


FIG. 144. Tracing the path of a ray of light through a glass prism.

Notice that *light passing through a prism is bent towards the base of the prism.*

(ii) Set up your 'ray apparatus' so as to give a narrow beam of light. Take a glass triangular prism, roughened on one of its triangular faces, and place it with the rough side downwards in the path of the ray as shown in Fig. 145. Trace the path of the ray of light through the prism.

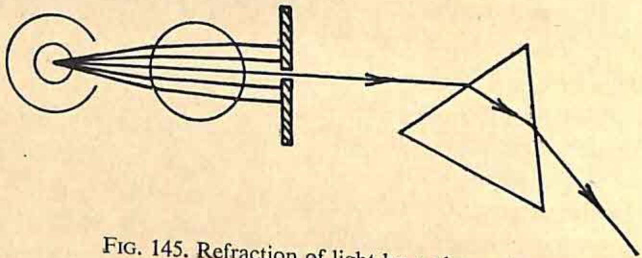


FIG. 145. Refraction of light by a glass prism.

(iii) Repeat the experiment with prisms of different angle, and notice that *a prism of large angle turns the ray of light more than a prism of small angle.*

LENSES

A lens is a piece of glass or other transparent material enclosed by two spherical surfaces.

Convex lenses are thicker at the centre than at the edge, and they cause parallel beams of light to converge.

Concave lenses are thicker at the edge than in the centre, and they cause parallel beams of light to diverge.

(*a*) Set up your 'ray apparatus' to give three narrow parallel beams on a sheet of paper. Place half a *convex* lens[1] (or a cylindrical convex lens) in the path of the light as shown in Fig. 146 (*a*). Notice that the parallel beams of light *converge* to a *focus* after passing through the lens.

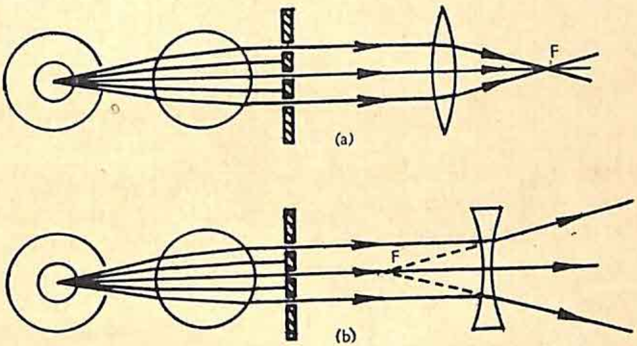


FIG. 146. The effect of lenses on parallel beams of light.

(*b*) Repeat your experiment using a *concave* lens, and notice that the parallel beams *diverge* after passing through the lens, as shown in Fig. 146 (*b*).

HOW A LENS ACTS

To understand how a lens acts, it is easiest to imagine a lens to be built up of a very large number of prisms of gradually increasing angle, as shown in Fig. 147. We have seen that a ray of light is bent towards the base of a prism, and also that it is bent more by a prism of large angle than by one of small angle. Hence, when a beam of parallel rays falls on a *convex* lens, the rays of light that fall near the edge of the lens are bent inwards more than those

[1] Spherical lenses, cut in half across their diameter (by using a glass-cutting diamond), give satisfactory results.

falling near the centre, and the result is a *converging beam* of light, as shown in Fig. 147 (*a*).

Conversely, when a beam of parallel rays falls on a *concave* lens, the rays of light that fall near the edge of the lens are bent outwards more than those falling near the centre, and the result is a *diverging beam* of light, as shown in Fig. 147 (*b*). *The point towards*

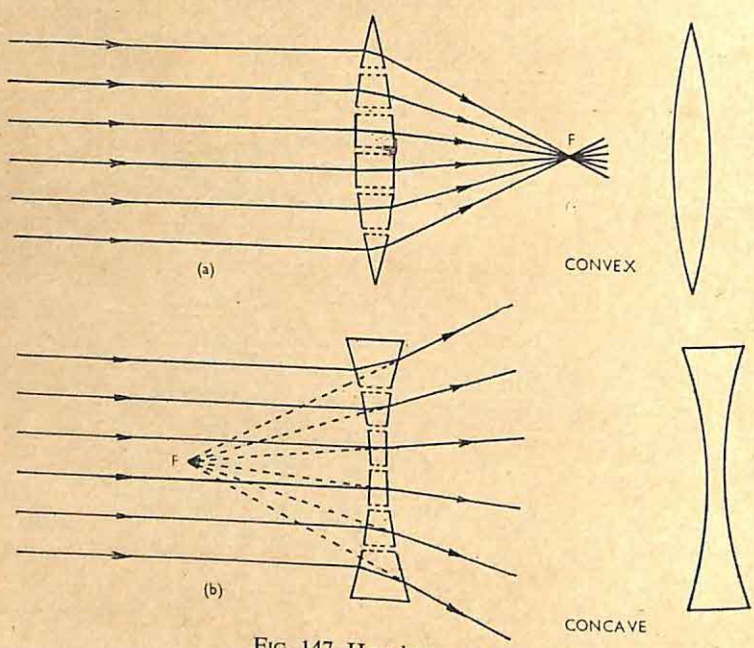


FIG. 147. How lenses act.

which all these rays converge (*or from which they appear to diverge*) *is called the focus of the lens, and the distance of this point from the centre of the lens is the focal length* (*f*) *of the lens.*

HOW TO FIND THE FOCAL LENGTH OF A LENS

(i) Take a *convex* (or *converging*) lens and support it in a lens-holder at the end of a metre-rule, as shown in Fig. 148. Move a white screen along the metre-rule until a clear image of a distant

object, e.g. a tree, building, or cloud, is seen on the screen. (Notice that the image is *real*, *inverted*, and *diminished*.) Measure the distance between the lens and the image: this is the *focal length* of the lens. $f = \ldots\ldots\ldots$ cm.

This reminds us of the use of a convex lens as a *burning-glass*. When such a lens is held between the Sun and a sheet of paper, in one position there is a bright spot of light on the paper, i.e. the light (and also the radiant heat) has been converged to the *focus*.

(ii) Set up your 'ray apparatus' to produce three narrow parallel

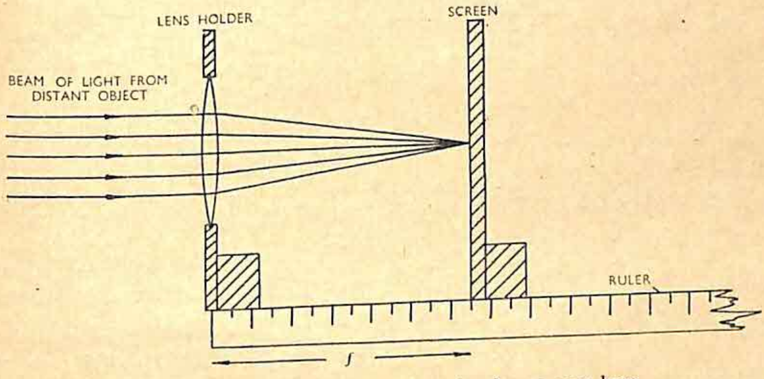


FIG. 148. Finding the focal length of a convex lens.

beams on a sheet of paper. Place half a *convex* lens in the path of the light so as to converge the parallel rays to a focus, as shown in Fig. 149 (*a*). Measure the distance between this focus and the centre of the lens. This is the *focal length* of the lens. $f = \ldots\ldots\ldots$ cm. (Notice that it is a *real* focus.)

(iii) Repeat your experiment with a *concave* lens. Mark the position of the lens and the path of the diverging rays. Remove the lens, and produce the diverging rays backwards to meet on the other side of the lens, as shown in Fig. 149 (*b*). Measure the distance between the focus and the centre of the lens. This is the focal length of the lens. $f = \ldots\ldots\ldots$ cm. (Notice that it is a *virtual* focus, as the image cannot be caught on a screen.)

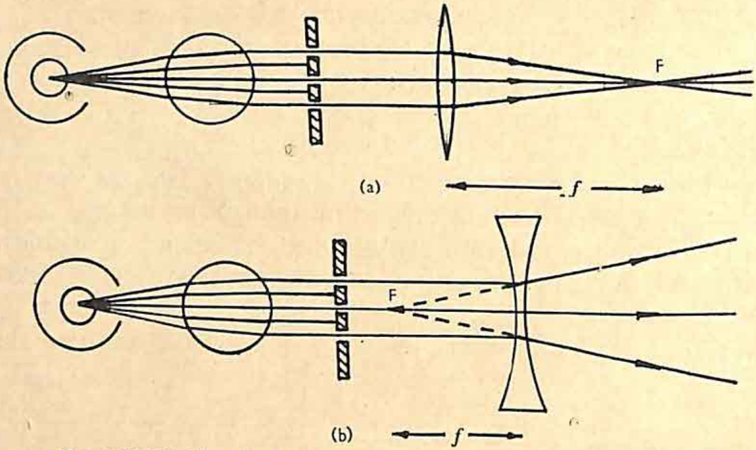


FIG. 149. Finding the focal lengths of lenses with the ray apparatus.

GEOMETRICAL CONSTRUCTION OF IMAGES FORMED BY LENSES

We have seen that it is a simple matter to find by geometrical construction the nature and position of images formed by spherical *mirrors*. The same thing can be done with *lenses*. As in the case of spherical mirrors, there are three rays whose paths are easily traced:

(*a*) *Any ray that passes through the centre of the lens goes straight on without being bent.*

(*b*) *Any ray parallel to the axis is bent so as to pass through the focus.*

(*c*) *Any ray passing through the focus is bent parallel to the axis.*

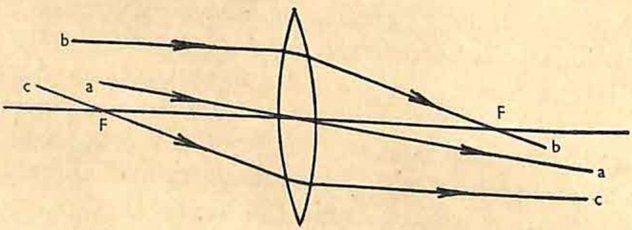


FIG. 150. Rays used in the geometrical construction of images.

These three rays are shown in Fig. 150, and if we draw any two of these rays, their point of intersection gives the position of the image of a point formed by the lens.

HOW TO FIND THE POSITION OF IMAGES FORMED BY LENSES

(i) In Fig. 151, O is the centre of a *convex* lens, F its focus, and AB an object standing on the axis of the lens, at a distance from the lens of *more than twice the focal length*. In order to find the position of the image of AB, AC is drawn through A parallel to the axis. This ray will be bent to pass through the focus, hence if we join CF and produce it, the image of A will lie somewhere along

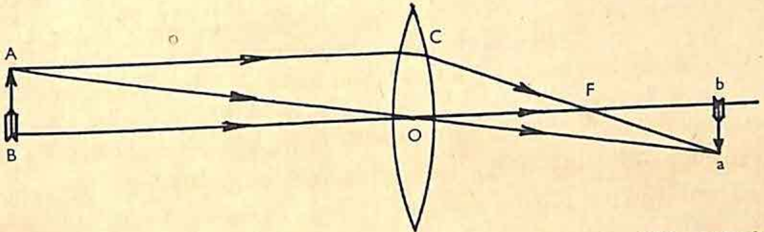


FIG. 151. Image formed when the object is at a distance greater than $2f$ from the lens.

CF, or CF produced. AO is drawn through A and the centre of the lens O, and this ray will go straight on. Hence the image of A lies along AO or AO, produced, i.e. the image of A lies at the point of intersection of CF and AO, produced. The image of B will lie somewhere along the axis, hence *ab* is the image of AB. Notice that *when the object is at a distance greater than 2f from a convex lens, the image is real, inverted, and diminished.*

Verify this with a convex lens of known focal length on the optical bench, placing the lens *more than twice its focal length* from the illuminated* object and then moving the white screen backwards and forwards until it receives a clear image of the illuminated object, as shown in Fig. 152. Compare the image on the screen with the illuminated object. This shows the principle of the ordinary photographic-camera (see also p. 233).

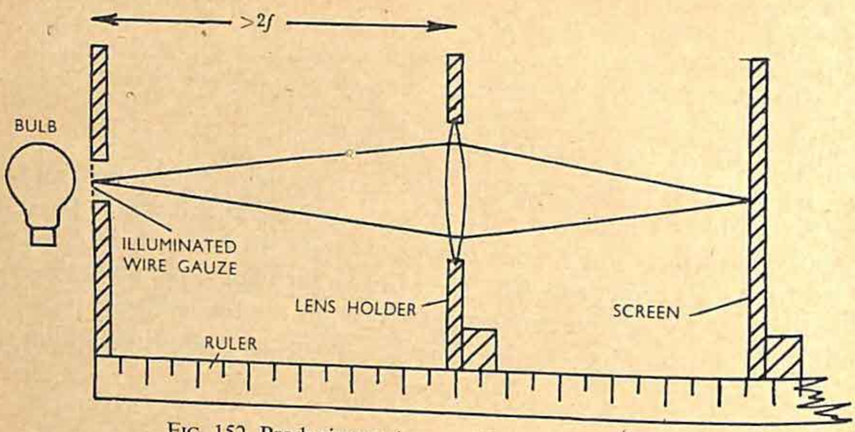


FIG. 152. Producing an image with the optical bench.

(ii) In Fig. 153, the object AB is at a distance *greater than f but less than* 2*f* from the lens. The position of the image *ab* is found by using the same construction as in (i). Notice that *when the object is at a distance greater than f but less than* 2*f from the lens, the image is real, inverted, and magnified.*

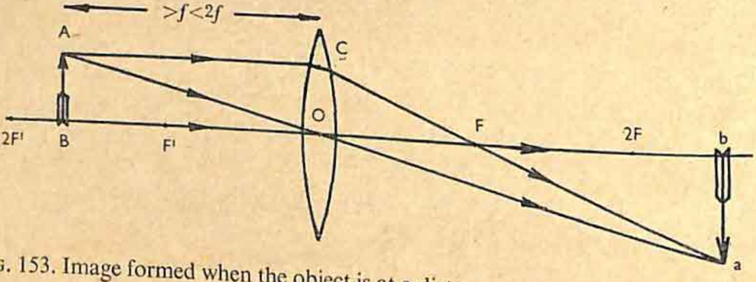


FIG. 153. Image formed when the object is at a distance greater than *f* but less than 2*f* from the lens.

Verify this with your convex lens of known focal length on the optical bench as in (i), placing the lens between *f* and 2*f* from the illuminated object. This is the principle underlying the projection of films and lantern*-slides† (see also p. 238).

(iii) In Fig. 154, the object AB is at a distance *equal to twice the*

focal length from the lens. Using the same geometrical construction, the image *ab* is found to be *real, inverted,* and *of the same size* as the object.

Verify this with your convex lens on the optical bench, placing the lens at $2f$ from the illuminated object. This shows the principle of the double-extension or copying camera (see also p. 233).

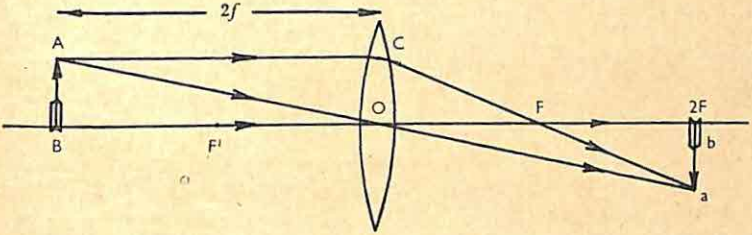


FIG. 154. Image formed when the object is at a distance equal to twice the focal length from the lens.

(iv) In Fig. 155, the object AB is *at a distance from the lens of less than the focal length.* Notice that the image *ab* is *virtual, upright,* and *magnified.*

Verify this with your convex lens on the optical bench and notice that you cannot receive the image on a screen, but can only see it by looking through the lens. This shows the principle of the

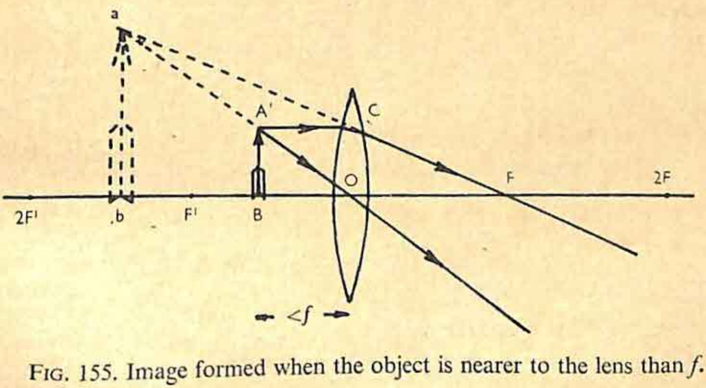


FIG. 155. Image formed when the object is nearer to the lens than f.

hand-lens or magnifying-glass, used for magnifying small objects (see also p. 240).

(v) Fig. 156 shows the nature and position of the image formed by a *concave* lens. Notice that *with a concave lens, the image is always virtual, upright, and diminished in size, whatever the relative positions of the lens and the object.*

Verify this with a *concave* lens on the optical bench and notice that you cannot receive the image on a screen, but can only see it through the lens. For the use of lenses in eye-glasses see pp. 235–236.

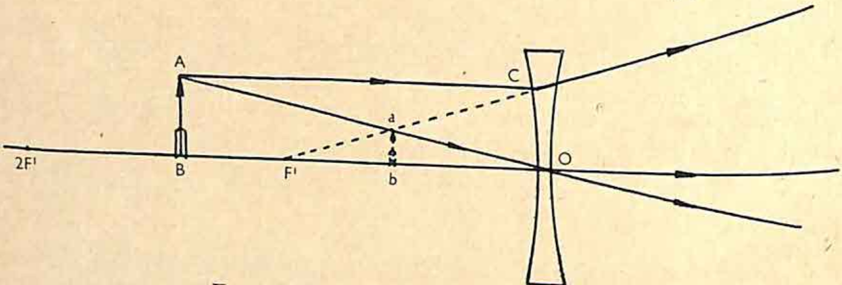


FIG. 156. Image formed by a concave lens.

THE MAGNIFYING POWER OF LENSES

The magnifying power of a lens is the ratio of the size of the image to the size of the object: i.e.

$$\text{MAGNIFYING POWER} = \frac{\text{SIZE OF IMAGE}}{\text{SIZE OF OBJECT}} = \frac{ab}{\text{AB}}$$

In all the Figs. 151–156, it is clear that AOB and *a*O*b* are 'similar triangles'*, therefore $\frac{ab}{\text{AB}} = \frac{\text{O}b}{\text{OB}}$; i.e.

$$\text{MAGNIFYING POWER} = \frac{\text{DISTANCE OF IMAGE FROM LENS}}{\text{DISTANCE OF OBJECT FROM LENS}}$$

OPTICAL INSTRUMENTS

THE PHOTOGRAPHIC CAMERA

If a piece of cardboard, with a small pin-hole through its centre, is held between an illuminated object and a white screen in a dark

room, a clear image of the object is formed on the screen, as shown in Fig. 157. If the screen is replaced by a photographic plate or film in a light-tight box with a small hole in the opposite side, we have a

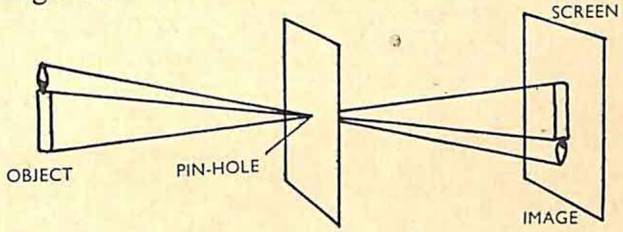


FIG. 157. Principle of pin-hole camera.

pin-hole camera, capable of taking very good photographs, provided that the exposure is sufficiently long.

If a *convex lens* is substituted for the pin-hole, we have an

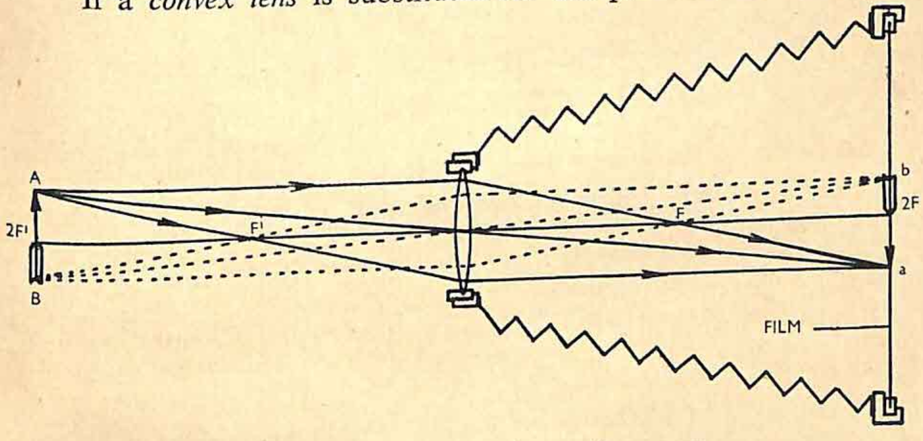


FIG. 158. Principle of double-extension camera.

ordinary *photographic camera* (see Fig. 158). When the lens is at a distance equal to its focal length from the plate or film, a clear image of a distant object is formed on the plate. If the object is nearer than about twenty feet from the camera, the lens is moved farther away from the plate, until, when the object is to be copied

life-size, the lens will be twice its focal length from the plate or film. That is to say, a *double-extension camera* is necessary for photographing small objects life-size.

A simple lens never gives a perfect image, because the outer part of the lens bends the rays slightly more, in proportion, than the part near the centre, hence the sharpest images are obtained by using only the middle of the lens. This is done by using a small opening or '*stop*'† in front of the lens. A longer exposure is needed when a small 'stop' is used, since less light enters the lens. This is no disadvantage when photographing still objects, e.g. buildings, but with moving objects the exposure must be short, therefore the 'stop'† must be large enough to admit plenty of light. Under such conditions, a carefully-made *compound lens* must be used if a sharp image is to be obtained.

THE HUMAN EYE

From the optical point of view, the human eye (see Fig. 159) is a camera in which the plate or film is replaced by a sensitive screen

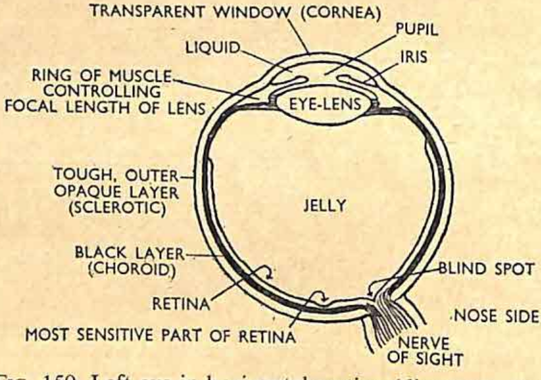


FIG. 159. Left eye in horizontal section (diagrammatic).

called the *retina*.† The *eye-lens* produces a real image on the sensitive nerve-endings of the retina, and the *nerve of sight* carries this impulse to the brain. In the photographic camera, a sharp image is obtained by varying the distance between the lens and the

film, but in the human eye this is not possible. Instead of this, the *focal length* of the *eye-lens* is varied. The eye-lens is soft and elastic and is surrounded by a ring of muscle. When this muscle contracts, the eye-lens becomes more convex, so that its focal length is reduced and clear images of near objects are produced on the retina. When the eye is viewing distant objects, the ring of muscle expands, the lens flattens out and its focal length is increased, so that clear images of distant objects are formed on the retina.

Just as a photographer uses a 'stop' to regulate the amount of light entering the camera, so the human eye has an *iris*† (the coloured part of the eye) with a circular hole, the *pupil*,† in the centre, which contracts or expands according to the brightness of the light. Our eyes are more sensitive, more complex, and more flexible than the best cameras. (We shall discuss the structure of the eye in more detail in Book Four.)

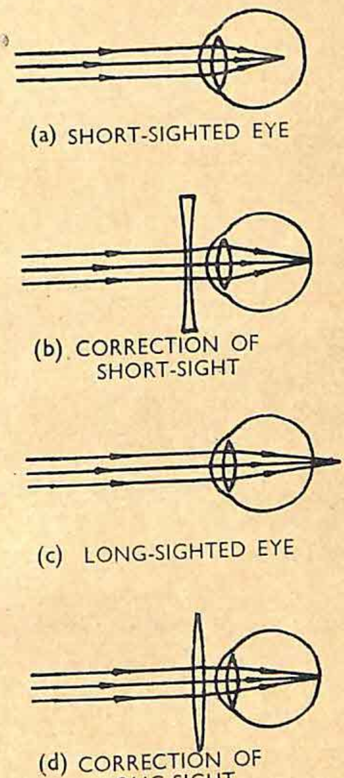


FIG. 160. Faults of eyesight and their correction.

FAULTS OF EYESIGHT AND THE USE OF EYE-GLASSES

A *short-sighted* person can only see objects clearly when they are near to him; and he cannot see clearly objects beyond a certain distance. This is because the transparent covering in front of the eyeball is too much curved, and parallel rays from a distant object are brought to a focus *in front of the retina*. In other words, the converging effect is too great, as shown in Fig. 160 (*a*). This can be corrected by placing a suitable concave

or diverging lens in front of the eye, so that the image of a distant object is formed on the retina (see Fig. 160 (b)). *A short-sighted person, therefore, needs eye-glasses with concave lenses.*

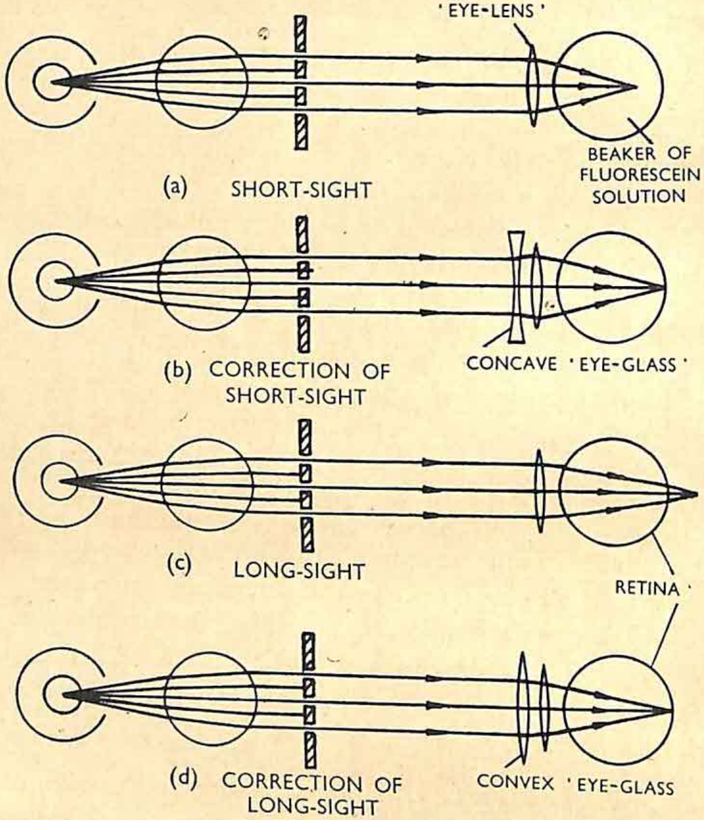


FIG. 161. Ray experiments to illustrate short-sight and long-sight and their correction.

Set up your 'ray apparatus' as shown in Fig. 161 (*a*), so that three narrow parallel beams of light are converged by a convex lens (representing the eye-lens) into a beaker or crystallizing-dish containing *fluorescein*† solution and standing on a black surface. Look vertically downwards into the beaker and move the lens back-

wards and forwards until you reproduce the conditions of *short-sight*. Then place a concave lens in front of the 'eye-lens' and move it backwards and forwards until the rays are brought to a focus on the back surface of the beaker (representing the retina), as shown in Fig. 161 (*b*).

A *long-sighted* person can see distant objects clearly but not near objects. This is because the transparent covering in front of the eyeball is not sufficiently curved, and rays from a near object are brought to a focus *behind the retina*. In other words, the rays are not converged sufficiently, as shown in Fig. 160 (*c*).

This fault can be corrected by placing a suitable *convex* or converging lens in front of the eye so that the image of a near object is formed on the retina (Fig. 160 (*d*)). *A long-sighted person, therefore, needs eye-glasses with convex lenses.*

Set up your 'ray apparatus' as shown in Fig. 161 (*c*), reproducing the conditions of *long-sight*. Then place a *convex* lens in front of the 'eye-lens' and move it backwards and forwards until the rays are brought to a focus on the 'retina', as shown in Fig. 161 (*d*).

A third kind of eye trouble often develops as people get older, when the eye-lens gets harder and less elastic, and the ring of muscle is unable to squeeze it sufficiently to make it more convex for looking at near objects. Older people, therefore, often need glasses with *convex* lenses for reading; in fact they often require two pairs of glasses, one for reading and one for viewing distant objects.

THE ADVANTAGE OF HAVING TWO EYES

If one of your eyes is covered up, you soon feel uncomfortable because your idea of *distance* is not good. You find, for example, that it is much more difficult to catch a ball, or to strike a nail with a hammer, when one eye is kept closed. When an object is viewed with two eyes, each eye receives a slightly different image because the eyes are set a little distance apart. If a piece of cardboard is held vertically with its edge towards you, when both eyes are used both sides of the cardboard are seen at once, and it is easy to form an

idea of its width. If only one eye is used, only the edge of the cardboard is seen and this gives no idea of its width.

An ordinary photograph represents what a one-eyed observer would see, and it appears 'flat', giving little idea of 'depth' or 'distance'. If two photographs are taken of the same view, using two cameras with their lenses the same distance apart as the human eyes, the two pictures are those that would be seen by the two eyes of a human observer. If these two photographs are placed side by side and viewed through a *stereoscope*,† as shown in Fig. 162, both pictures are combined into one and this gives an idea of distance that is entirely lacking in an ordinary photograph.

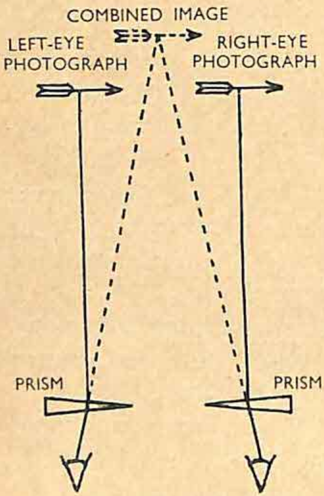


FIG. 162. Principle of stereoscope.

For the same reason, *field-glasses* (or *binoculars*†) give a better idea of distance than *telescopes*.

THE OPTICAL PROJECTOR (OR 'MAGIC LANTERN')

An *optical projector* for showing lantern-slides or film-strips is the converse of the photographic camera. In the camera we have a large distant object producing a diminished, inverted image behind the lens. In the optical projector the object is the brightly illuminated lantern-slide, and a magnified, inverted image is produced on the distant screen, as shown in Fig. 163. There is a powerful source of light (either a strong electric bulb or an electric arc) with a concave mirror behind it. A convex lens called the *condenser*† concentrates the light on the *lantern-slide*, thus forming a brightly illuminated object. In front of the slide, and at a distance slightly greater than its focal length from it, there is another convex lens called the *objective*.† This produces a *real*, *inverted*, and *magnified* image

of the slide on the screen. If the image is to appear on the screen the right way up, the slide must be put into the projector upside-down. The image is focused on the screen by moving the *objective* backwards or forwards.

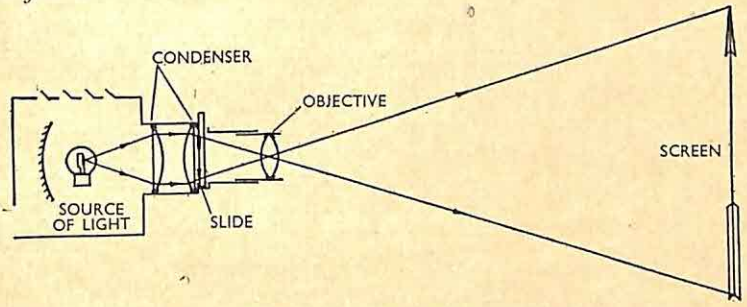


FIG. 163. Principle of optical projector.

THE CINEMA PROJECTOR

The apparatus used for projecting 'moving' pictures is simply an optical projector specially arranged to change the slides very quickly. The *film* consists of a large number of separate small pictures (taken by a special camera at intervals of a fraction of a second) which pass quickly between the condenser and the objective. As each single picture comes between these lenses, the objective is uncovered for a fraction of a second, and an image is produced on the screen. The objective is then covered for a fraction of a second until the next picture is in position between the lenses, and when the next picture is in the correct position, the objective is again uncovered and another image is produced on the screen. In this way a rapid succession of still images (about sixteen per second) is produced on the screen, with dark intervals between them. We do not notice that the screen is dark between the images (unless the film is running too slowly) because the human eye continues to 'see' the images a fraction of a second after they disappear, hence the pictures on the screen appear to be continuous, combining to produce the effect of a 'moving picture'.

THE MAGNIFYING GLASS (OR SIMPLE MICROSCOPE)

We have seen (on p. 231) that if an object is placed behind a convex lens, but nearer to it than its focus, a *virtual*, *upright*, and *magnified image* is produced, farther away from the lens than the object.

In order to use a convex lens as a magnifying glass, therefore, we place the eye close to it (steadying the lens against the side of the nose), and hold the object behind it *at a distance not greater than the focal length of the lens*, as shown in Fig. 164. The object is then moved backwards and forwards until it comes into 'sharp focus'. By placing the eye close to the lens we get a large *field of view*.

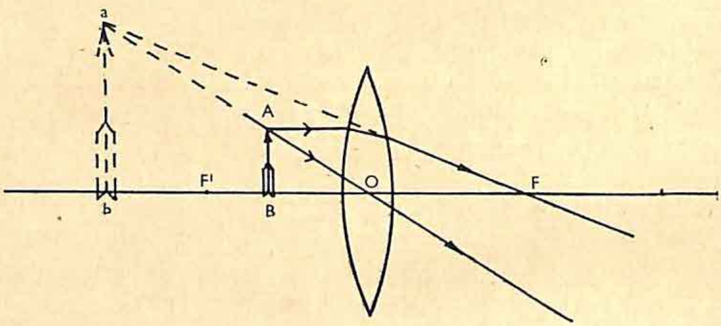


FIG. 164. Principle of magnifying-glass.

This arrangement is the principle of the *eyepiece*† used in microscopes, telescopes and other optical instruments.

THE COMPOUND MICROSCOPE

A greater magnification can be obtained by using two convex lenses arranged to form a *compound microscope*. As shown in Fig. 165, a convex lens, of short focal length, called the *objective*, is placed at a distance *slightly greater than its focal length* away from the object, forming a *real*, *magnified*, and *inverted* image. This image is viewed through another convex lens, called the *eyepiece*, when a *virtual*, *magnified*, but still *inverted* image is seen.

Using the optical bench, arrange a convex lens of short focal length to produce a real, inverted, and magnified image of the

illuminated object on a translucent screen, i.e. place the lens at a distance of between f and $2f$ from the object. Use a second convex lens, also of short focal length, as an *eyepiece* to magnify the image produced on the screen by the *objective*. Then, leaving the two lenses in position, remove the translucent screen, and you have a model compound microscope. Notice that with simple, cheap lenses, the image looks out of shape and has coloured edges.

Some compound microscopes have a magnifying power of 2,000 times, but with such high magnifications the image becomes very

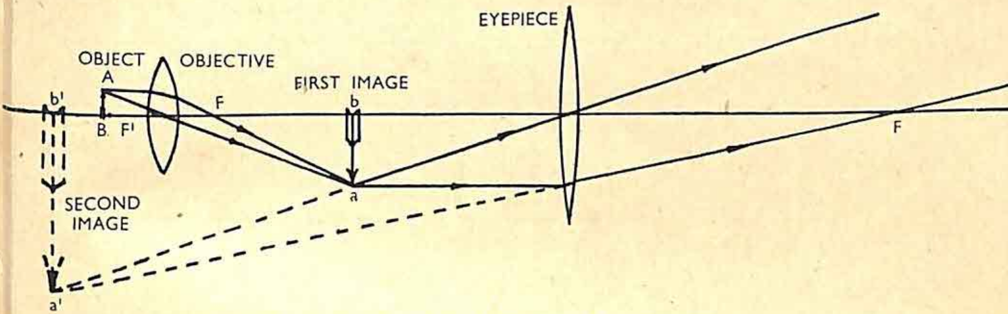


FIG. 165. Principle of compound microscope.

faint, because the light that is concentrated on the small object (by the *condenser*) is spread out over such a large area in the image. Practical instructions for using a laboratory microscope are given on pp. 276–278.

THE SIMPLE TELESCOPE

It is often necessary to use a *telescope* in order to see a distant object more distinctly. The simplest type consists of two convex lenses: one a large lens of long focal length, called the *objective*, and the other a smaller lens of short focal length, called the *eyepiece*.

As shown in Fig. 166, the *objective* forms a *real*, *inverted*, *reduced* image of a distant object at its focus, just like the lens of a camera. This image is then viewed through the eyepiece of the telescope, which is a magnifying glass producing a *virtual*, *magnified*, and *inverted* image of the distant object.

To set up a model telescope on the optical bench, arrange a convex lens of long focal length to produce an image of a distant object on a translucent screen. Arrange a second convex lens, of short focal length, as an eyepiece to magnify the image produced on the screen by the objective. Then, leaving the two lenses in position, remove the translucent screen and notice the improvement.

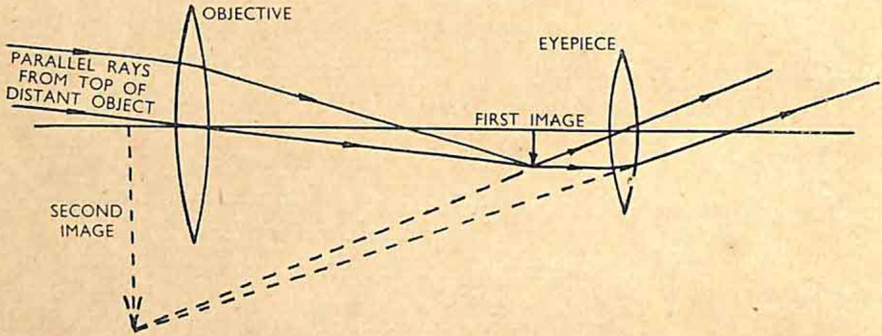


FIG. 166. Principle of simple telescope.

THE UPRIGHT-IMAGE TELESCOPE

The *simple telescope* gives an *inverted* image. This is no disadvantage when viewing heavenly bodies, but for viewing distant objects on the Earth it is much more convenient to see an upright image. This upright image is produced by adding an extra convex lens of short focal length placed at a distance equal to *twice its focal length from the image produced by the objective*, forming an upright image of the same size, which is then viewed by the eyepiece. Fig. 167 shows the principle of the upright-image telescope.

Using three suitable convex lenses, set up a model upright-image telescope on the optical bench, following the same method as in the case of the simple telescope.

SIMPLE FIELD-GLASSES

If an upright-image telescope is to have a large magnifying power it must be long, and length is a disadvantage in many ways, e.g. it

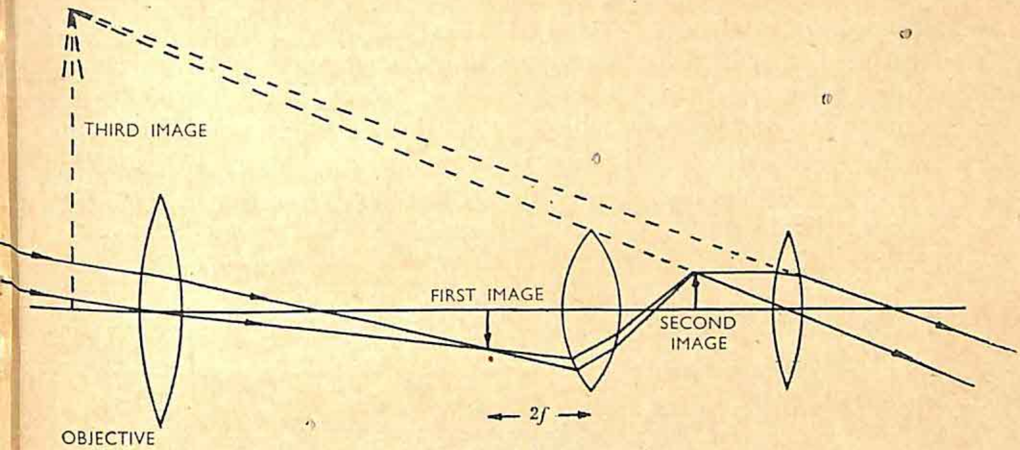


FIG. 167. Principle of upright-image telescope.

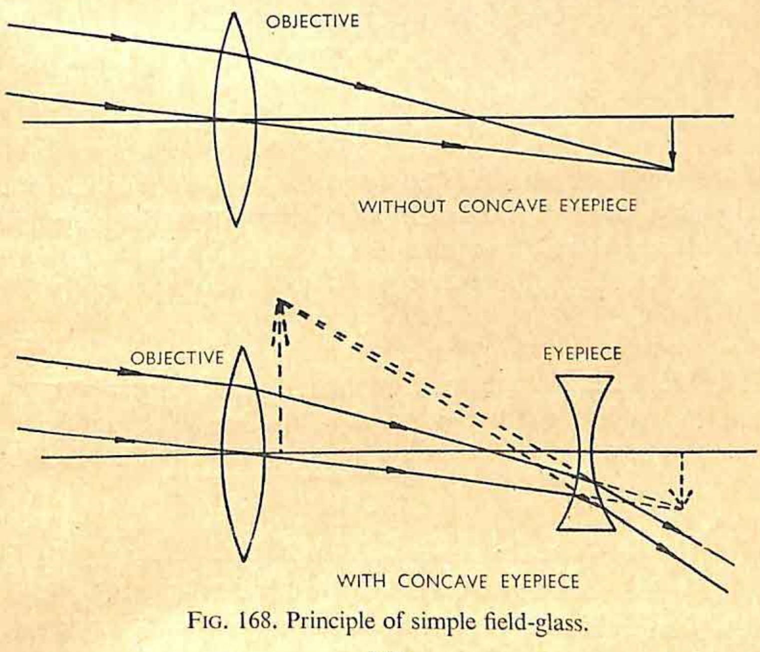


FIG. 168. Principle of simple field-glass.

makes the instrument awkward to carry about and difficult to hold steady when looking through it. If a *concave* or diverging lens is used as the eyepiece, as shown in Fig. 168, a virtual, upright, and magnified image is produced, and this arrangement is used in cheap field-glasses, which can be made much shorter than telescopes, although they have only a small field of view. Set up a model field-glass on the optical bench.

PRISMATIC FIELD-GLASSES

Prismatic field-glasses (see Fig. 169) have the advantages of upright-image telescopes without their disadvantages. In this form

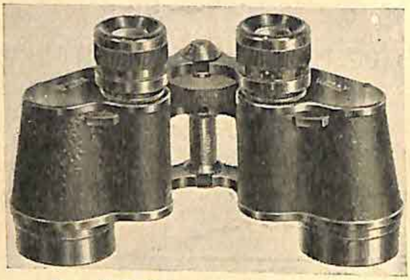


FIG. 169. Prismatic field-glasses.

of field-glass the rays of light are made to pass backwards and forwards between two right-angled glass prisms, as shown in Fig. 170, so that the total length of the instrument is only about one-third

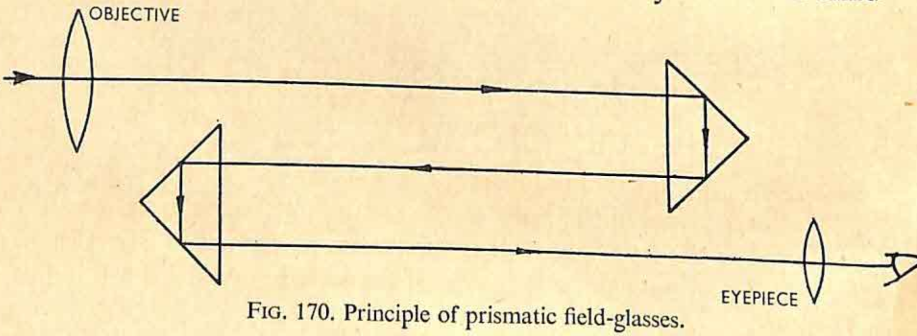


FIG. 170. Principle of prismatic field-glasses.

that of a telescope of the same power. The right-angled prisms also produce an upright image for the eyepiece to magnify. Field-glasses have two telescopes side by side, one for each eye, and therefore give a better idea of depth and distance. Prismatic field-glasses (or prismatic binoculars) usually have their objectives set wider apart than the eyes and therefore give a still better idea of distance and depth.

COLOUR

DISPERSION

In our earlier experiments, we noticed that objects viewed through prisms and simple lenses show coloured edges that remind us of the similar colours seen in rainbows.

In 1666, Sir Isaac Newton allowed a beam of sunlight to enter a

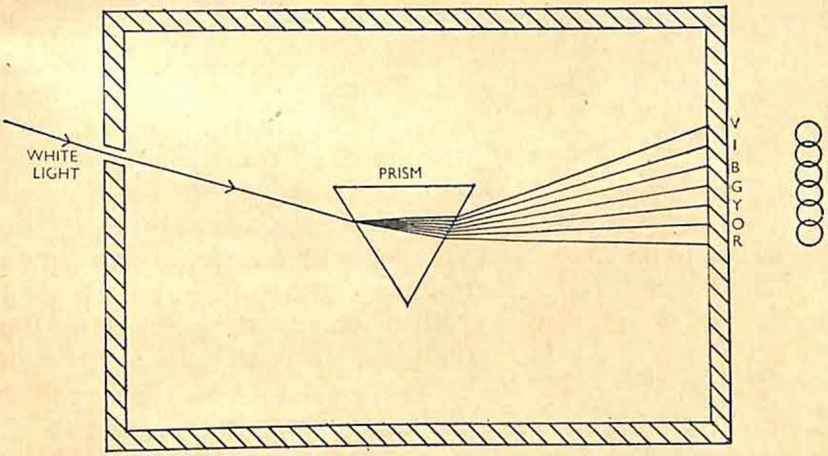


FIG. 171. Newton's analysis of white light by dispersion.

dark room through a small round hole in one side of the room. He held a glass prism in the path of the beam, and bent the light upwards on to the opposite wall of the room as shown in Fig. 171. Instead of getting a circular image of the sun, he obtained a band of colour.

From this experiment, Newton discovered that *white light is a mixture of light of several colours*. This splitting up of white light into different colours by refraction is called *dispersion*.†

Newton called this coloured band of light a *spectrum*,† and in

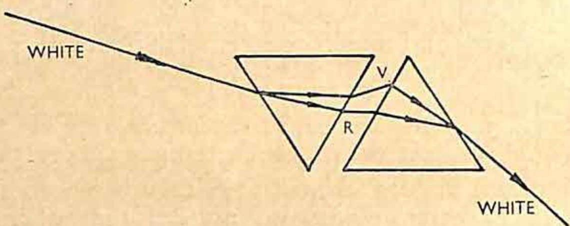


FIG. 172. Newton's analysis and re-synthesis of white light.

the spectrum of sunlight the different colours are arranged in the same order as the colours of the rainbow, i.e. *violet*, *indigo* (deep blue), *blue*, *green*, *yellow*, *orange*, and *red*. (Remember the 'word' *vibgyor* formed by the first letter of each colour.) These were formerly called the seven *primary colours*.

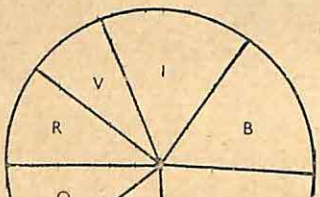


FIG. 173. Newton's colour disc.

To verify that white light is a mixture of all these colours, Newton allowed the spectrum formed by this prism to pass through a second similar prism, turned the other way round, as shown in Fig. 172. He found that the colours were mixed again by the second prism, producing white light once more. That is, the first prism *analysed* white light and the second prism *synthesized* it.

Another striking experiment to show the synthesis of white light from violet, indigo, blue, green, yellow, orange, and red, is *Newton's colour disc*. This is a disc of cardboard painted with the different colours of the spectrum, in their correct proportions, as shown in Fig. 173. If the disc is brightly illuminated and then rotated* at great speed, the colours

appear to mix together; and finally, when the speed is fast enough, the disc appears white.

THE EXPLANATION OF DISPERSION

We have learnt that refraction is caused by the varying speed of light in different transparent media. In dispersion experiments with prisms, however, we find that light of different colours is turned through different angles, *red light being bent least and violet most.* This is because *red light travels faster than violet light*, so that, in passing through a glass prism, violet light is slowed down more than red light and undergoes greater refraction.

DISPERSION EXPERIMENTS WITH PRISMS

(i) Hold a triangular glass prism in the path of a beam of sunlight and produce a spectrum on a white wall or ceiling. Notice that the seven colours are not clearly separated, i.e. you have produced an *impure spectrum.* As in Newton's experiment (see Fig. 171), you have a series of separate images of the sun, overlapping each other.

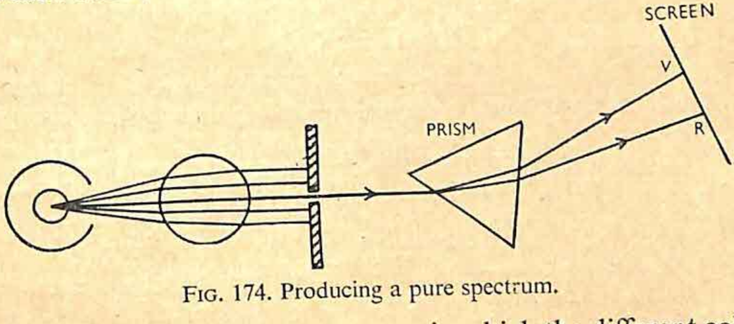


FIG. 174. Producing a pure spectrum.

(ii) In order to get a *purer spectrum*, in which the different colours do not overlap so much, set up your 'ray apparatus' as shown in Fig. 174, so as to produce a very narrow parallel beam of white light on a sheet of white paper on the bench. Place a glass prism in the path of the ray of white light and catch the resulting spectrum on a white screen (or better still, on a translucent screen).

Turn the prism slowly until you find the position in which the light undergoes least refraction, and notice that the brightest spectrum is obtained with the prism in this position. Examine this small but pure spectrum on the screen and notice the relative bending of the red and violet rays on the sheet of paper.

(iii) Repeat Newton's synthesis of white light by placing a second similar prism as shown in Fig. 175 (*a*).

(iv) Re-combine the coloured rays by means of a concave cylindrical mirror as shown in Fig. 175 (*b*).

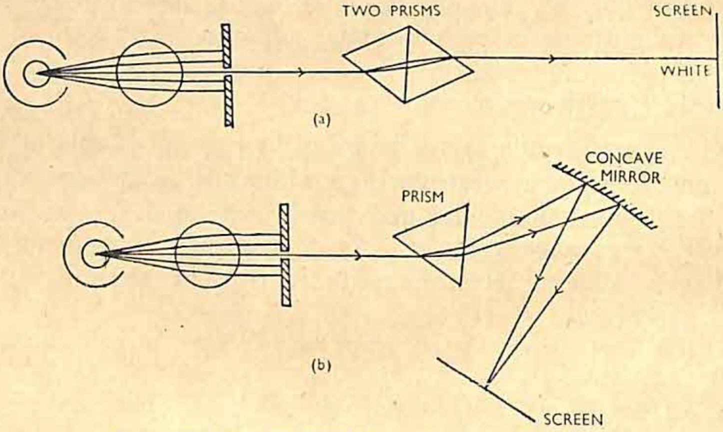


FIG. 175. Analysing and re-synthesizing white light.

(v) Produce a spectrum on the screen as in Experiment (ii) and place in front of the prism (*a*) a red film, (*b*) a blue film, (*c*) a green film, (*d*) both red and blue, (*e*) red and green, (*f*) green and blue. Notice carefully the effect on the spectrum in each case.

RAINBOWS

A *rainbow*† is formed by the *refraction* and *reflection* of the Sun's rays by drops of rain. You will have noticed that rainbows are only seen when rain and sunshine are both present at the same time. You only see a rainbow *when you have your back to the Sun* and *when rain is falling in front of you*. When a ray of sunlight enters a

raindrop, it is refracted, dispersed, and reflected as shown in Fig. 176. On reaching the other side of the raindrop, one of these coloured rays is reflected to the observer's eye, so that he sees only the colours produced by those raindrops making a suitable angle with the Sun and his eye. Such raindrops will lie in a cone whose apex* is at the observer's eye. This explains the characteristic curved form of rainbows. The raindrops on the inside of the rainbow reflect only violet light to the observer's eye, while those on the outside reflect red light only. Fig. 176 shows two such drops.

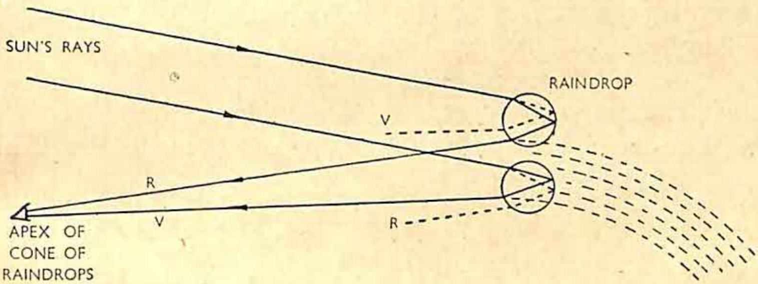


FIG. 176. Dispersion by raindrops to form a rainbow (diagrammatic).

THE COLOUR OF TRANSPARENT MATERIALS

If a piece of red glass or film is placed in front of the slit used for producing a spectrum, all the colours of the spectrum disappear *except the red.* Similarly, if a piece of blue glass is held over the slit, all the spectrum disappears except the blue. If both red and blue glasses are placed over the slit, one on top of the other, all the spectrum disappears. This shows that a coloured transparent material owes its colour to the fact that it *absorbs* some of the constituent colours of white light and only transmits the remainder. Thus, the colour of red glass is due to the fact that *it absorbs all the other colours of the spectrum except red.* Ordinary glass appears colourless because it transmits all the colours of the spectrum equally without absorbing any colour. For some purposes (e.g. photography), coloured glasses and films are called *colour filters*

(or *light filters*) because they act like a filter in holding back light of certain colours and transmitting other colours.

Green leaves get the energy they require for photo-synthesis by absorbing part of the light that falls on them. If a *spectroscope*† (an instrument for producing and viewing a pure spectrum) is available you can find out which part of the light is absorbed by chlorophyll. Hold a solution of leaf-green in alcohol (or, better, in acetone†) between the slit of the spectroscope and a white light, and notice that *dark bands* appear in the spectrum. There is one distinct *absorption-band* near the red end of the spectrum and this red light supplies the energy for photo-synthesis (and therefore for all living things). There is also some absorption in the blue and violet parts of the spectrum, but this light is not used to supply energy. The blue and violet rays of sunlight are harmful to plant cells (they also cause sunburn in Man) and they are absorbed by one constituent of chlorophyll.

MIXTURES OF COLOURED LIGHTS

The apparatus shown in Fig. 177 (i) can be used to show the effect of mixing light of different colours. The rectangular box has three small windows covered with *red*, *blue*, and *green* films or 'light filters'. There is an electric lamp behind each window. A white screen is placed about a foot in front of the coloured windows, and a triangular piece of wood, or a wooden cone, is placed between the box and the screen. When the lamp behind the *blue* window is switched* on (in a dark room) the screen is blue and the cone casts a black shadow. If the lamp behind the *red* window is also switched on, the screen is *reddish-purple* and there are two shadows, the one cast by the red light being blue (since it receives blue light only) and the one cast by the blue light being red (since it receives red light only). If the cone is moved so that the two shadows overlap, there is a black shadow in the middle (since this region receives no light). If the red window is now darkened and the lamp behind the *green* window is switched on (without switch-

ing off the blue light), the screen is *greenish-blue* and there are two shadows, one blue and the other green.

If all three lamps are now switched on, so that the screen receives *blue*, *red*, and *green* light, the general background of the screen is *white*, and if the cone is in a suitable position, there are three shadows as in Fig. 177 (ii). The shadow cast by the green light (which receives blue light and red light) is *reddish-purple*; that cast by the red light (which receives green light and blue light) is

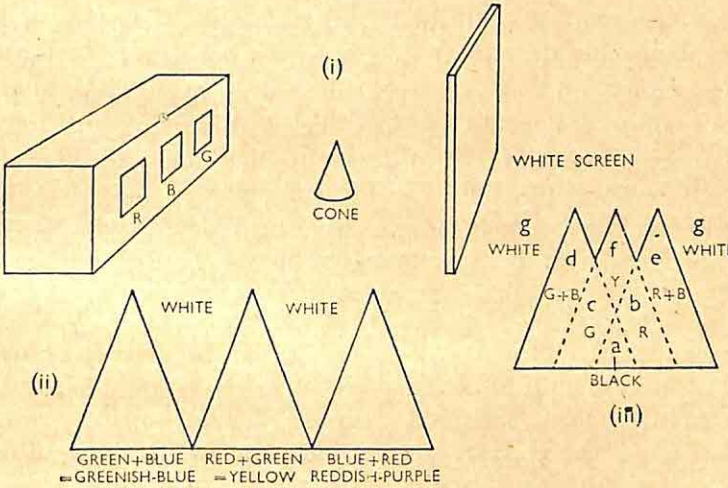


FIG. 177. Mixing lights of different colour.

greenish-blue; and that cast by the blue light (which receives red light and green light) is *yellow*. If the cone is moved so that the shadows overlap as in Fig. 177 (iii), it is possible to distinguish seven different regions: (*a*) black (receiving no light at all), (*b*) red (receiving only red light), (*c*) green (receiving only green light), (*d*) greenish-blue (receiving green and blue light), (*e*) reddish-purple (receiving red and blue light), (*f*) yellow (receiving red and green light), and (*g*) a white background (receiving blue, red, and green light).

This experiment shows that *by mixing LIGHTS of the three*

colours, blue, red, and green, in suitable proportions, any colour can be obtained. Blue light, red light, and green light are now described as the three primary colours† of light and it is impossible to obtain either blue, or red, or green light by mixing any other coloured lights together.

It is important to realize that *the colour of a mixture of coloured LIGHTS is due to the addition of the constituent colours.*

THE COLOUR OF OPAQUE MATERIALS

Using a large spectrum on a white screen in a darkened room, try the effect of holding different coloured materials, e.g. pieces of coloured wool, matchbox or similar labels, in the different parts of the spectrum. Notice that (*a*) if a piece of white paper is held in the spectrum, *it reflects all the different colours equally well*; (*b*) if a piece of red wool is held in different parts of the spectrum, *it appears black in all the colours except red*; (*c*) a piece of blue wool appears black in all the colours except blue; (*d*) a green leaf appears black in all the colours except green. It is clear that the *red material appears red because it reflects red light and absorbs all other colours.* Similarly, a green leaf reflects only the green part of daylight and absorbs all the other colours.

Hence, the colour shown by an OPAQUE MATERIAL in daylight is due to the absorption of all the constituents of white light except the colour that is reflected. If a surface *reflects* all the constituents of white light equally, it appears *white*. If it *absorbs* all the constituent colours, it appears *black*.

The primary colours of *paints* (and of *inks* used for three-colour printing) are blue, red, and yellow. In three-colour printing, three photographs are made of the coloured object. For the blue printing-plate, the lens of the camera is covered with a red light-filter, for the red printing-plate a green filter is used, and for the yellow printing-plate a blue filter. The painter's and printer's primary colours blue, red, and yellow are said to be *complementary*† to the three primary colours of light—red, green, and blue, for when each of these pairs of coloured *lights* (e.g. yellow and blue) is mixed,

white light is produced *by addition*. But when we mix blue and yellow *paints* we get green paint (and not white paint) because the blue paint absorbs the red, orange, and yellow part of the spectrum, while the yellow paint absorbs the blue, indigo, and violet. Hence the only colour that escapes this double absorption is green. So a mixture of blue and yellow paints reflects only green light and *the colour of any mixture of coloured paints or inks is due to subtraction* of some of the constituent colours from white light.

Remember, therefore, that '*colour is always a step towards darkness*', for colour is produced only by removing some of the constituents of white light.

THE COLOUR OF THE SKY

The Sun is a white-hot sphere that gives out light of all *wave-lengths*.[1] This light has to pass through the atmosphere before falling on the Earth's surface. Some of it is scattered by gas molecules and dust particles in the air. The shorter light-waves are scattered more than the longer waves and, as a result, when we look up into a clear sky (but not at the Sun itself) we are mainly receiving scattered light of short wave-length, i.e. we see a *blue* sky.

When the Sun is low in the sky—at dawn or sunset—the light coming from it to our eyes has to pass through a greater thickness of air than at mid-day. In so doing, most of the blue and green rays are removed by the scattering process mentioned above, and only the red and orange parts of the spectrum reach our eyes. The sunset is particularly red if the air contains a lot of water droplets or dust particles. During heavy dust-storms and bush fires, the Sun often appears red even when it is high in the sky.

The effect of the size of the particles that scatter the light is noticed when we compare the *blue* colour of fresh cigarette smoke with its *grey* appearance when it is puffed out from the mouth. The

[1] Light consists of *electro-magnetic waves*, and variations in the *wave-length* produce different sensations in the eye, corresponding to different *colours*. The *speed* of each different colour divided by its *frequency* gives the *wave-length* for light of that colour. Wave-length is longest at the red end of the spectrum.

moist smoke particles issuing from the mouth are larger than the dry smoke particles from the burning end of the cigarette and they scatter some of the longer light-waves as well as the shorter blue ones.

The blue colour of the sea is partly due to reflection from the sky and partly due to the scattering of short light-waves by small suspended particles and by water molecules. If the water contains still larger particles of sand, or air-bubbles, then it may appear green.

COLOUR-BLINDNESS

When white light is split up by a prism into its constituent rays of different wave-length, we see a spectrum of different *colours*. The eye and the brain share the power of distinguishing between rays of different wave-length. Some people, however, have this power less well-developed than others, and they are said to be 'colour-blind'. One group of such 'colour-blind' people cannot distinguish yellow and orange colours from reds and greens. Others see as yellow all the colours red, orange, yellow, and green, while they see blue, violet, and purple as blue. A blue-green colour is seen as grey. Such people are unable to distinguish a green light from a red light, and for this reason, railway and shipping companies test their officers for colour-blindness. The number of completely colour-blind people is, however, comparatively small.

LIGHT AND LIVING THINGS

In Book Two we have already discussed the importance of light to living things, and we know that the green plant is able to absorb light energy and store it up as chemical energy in food substances. Such substances are essential to both plants and animals. The process of photo-synthesis is possible only in those plants that contain the green colouring-substance *chlorophyll*. When white light falls on chlorophyll contained in the green *plastids*† (or *chloroplasts*) the red and blue light rays are absorbed and their energy is used in carrying out the reaction by which water and carbon dioxide yield oxygen and a carbohydrate. As we would

expect, light also has a marked effect on the growth of plants. Not only does it bring about growth in *dry weight* (owing to the formation of solid organic compounds from water and gaseous carbon dioxide), it also affects the rate of growth in length and the direction of growth. Plants usually place their stems and leaves in a position which ensures* that the maximum amount of light falls on their green parts. We shall discuss some of these growth movements later (in Book Four). In many other ways plant life is closely connected with light, e.g. the regular daily alternation of light and darkness has strange and little understood effects on the life of flowering plants. We know that length of day (which often varies with the seasons, in places away from the Equator) decides the date when different plants come into flower. This also explains why some plants that flower in summer in England (where they have over 16 hours of daylight) never flower in the tropics (where the hours of daylight are shorter). Also, different plants require light of different brightness, which partly explains why some can live in dense shade, while others do best when exposed to full sunlight.

Animals, also, are usually dependent upon light; indirectly because they get their food, in one way or another, from green plants, but more directly because many of them have special sense organs, eyes, that enable them to find their way about in search of food, mates, and homes. There are a few of the 'lower' animals that have actually evolved the power of *producing* light (e.g. glow-worms† and fire-flies,† by means of an active oxidation process, produce light with which they can signal to the opposite sex). But in most animals, the sense-organs connected with light are *receiving organs* (or *receptors*), and in Man and other 'higher' animals, the eye is a very complex and sensitive organ.

Chapter V

MAGNETISM

Over 2,000 years ago, it was known to the ancient Greeks that pieces of a black mineral, found near the town of Magnes, had the property of attracting small pieces of *iron*. Pieces of this mineral, which is an oxide of iron now called *magnetite*,† always set themselves in the same direction when hanging freely. For this reason, the mineral became known as *lode-stone*† (or 'lead-the-way' stone). It was discovered that *artificial magnets* could be made by stroking pieces of steel with these natural magnets, and men began to use such artificial magnets for fixing direction, for *when a magnet hangs freely, it sets itself in a north and south direction*. Nowadays, artificial magnets are made by passing an electric current round steel rods (see pp. 270–273).

TO EXAMINE THE PROPERTIES OF MAGNETS

(i) Examine a piece of magnetic iron ore that has been dipped in iron filings. Notice that most of the iron filings cling near the *ends* of the lode-stone and very few near the middle. The parts where the filings cling thickest are called *the poles† of the magnet*.

Small, cylindrical bar-magnets of cobalt-steel† (e.g. 2 in. by ¼ in.) are most suitable for the following experiments.

(ii) Bring a bar-magnet near small pieces of wood, glass, paper, brass, iron, nickel, cobalt,† etc.

Which of these substances shows *magnetic* properties, i.e. can be attracted by a magnet?. . . . .

(iii) Support a bar-magnet on a pivot,* as shown in Fig. 178, so that it is free to swing horizontally. Notice that the magnet comes to rest pointing in a north and south direction, i.e. *in the magnetic meridian*.* Mark the *north-pointing* pole (or N-pole) of the magnet.

Mark the N-pole of a second similar bar-magnet in the same way. With one bar-magnet supported on the pivot, bring the N-pole of the second magnet near the N-pole of the pivoted magnet.

What happens? ....

Now bring the S-pole of the second magnet near (*a*) the N-pole of the pivoted magnet, (*b*) the S-pole of the pivoted magnet.

What happens? (*a*) ....

....

(*b*) ....

....

This illustrates the *first law of magnetism*:—

*Like poles repel**: *unlike poles attract.*

Lay a cylindrical bar-magnet on a smooth bench and lay another similar magnet alongside it (*a*) so that *unlike poles are together*, (*b*) so that *like poles are together.*

What happens? (*a*) ....

....

(*b*) ....

....

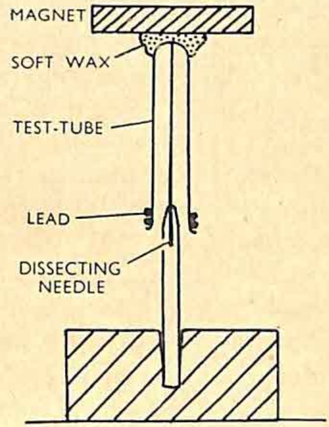


FIG. 178. Bar-magnet on pivot.

(iv) Take a steel rod (e.g. a bicycle-spoke) that is un-magnetized (test this by dipping the rod in iron filings) and balance it on a pivot as in Fig. 178.

Does it set itself in any particular direction? ....

Now remove the steel rod from the support, lay it on the bench, and stroke it from one end to the other with one pole of a bar-magnet (as shown in Fig. 179). Test it for magnetism by dipping in iron filings, and then replace it on the pivot.

In what direction does it set itself? ....

Any piece of steel can be magnetized in this way by stroking it *in one direction with one pole of a magnet.*

(v) Hammer or heat the magnetized rod and then test it for magnetism. Is it still magnetic?..........................

MAGNETIC TESTS

It is sometimes necessary to test a piece of metal to find out (*a*) whether it is a magnet, (*b*) whether it has magnetic properties but is not magnetized, and (*c*) whether it is non-magnetic. This is easily done by holding each end of the rod, in turn, near the N-pole of a pivoted bar-magnet or compass needle. If *one end attracts* this N-pole and *the other repels it*, then the piece of metal is a *magnet*. *If both ends* of the piece of metal attract the N-pole of the pivoted bar-magnet, then it is of *magnetic material but not magnetized*. If *neither end* of the piece of metal attracts the N-pole of the pivoted bar-magnet, then the piece of metal is of *non-magnetic material*.

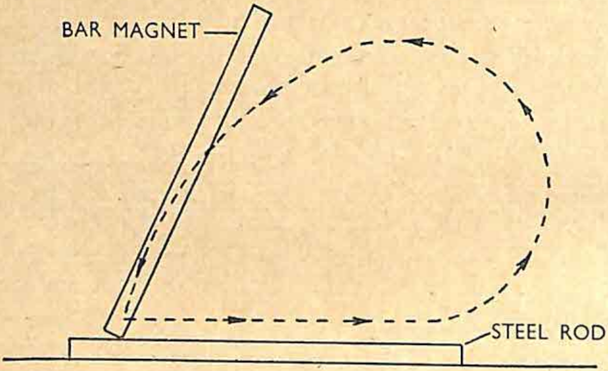


FIG. 179. Magnetizing by stroking.

MAKING MAGNETS

(i) *By Stroking*. This method has been described on p. 257 and is illustrated by Fig. 179. Notice (*a*) that one pole of the magnet is used continuously for stroking, (*b*) that stroking is in one direction only, (*c*) that the magnet is moved with a circular motion as shown by the arrows in Fig. 179, (*d*) that opposite polarity† is produced at the end of the rod where stroking ends.

(ii) *Electrical Method*. When a strong *direct current* of electricity is passed through a coil of covered copper wire wound round a

steel bar, a strong bar-magnet is produced. This is the modern method of making magnets and will be discussed in more detail later (see pp. 270-273).

MAGNETIC INDUCTION

(i) Hang two 'soft' iron nails (whose 'heads' have been cut off) side by side from the N-pole of a bar-magnet (see Fig. 180). Notice that the nails become magnets and that their free ends repel each other (as shown in Fig. 180 (i)). Test this by pushing the free end of one nail towards the other nail; the latter moves away (see Fig. 180 (i)).

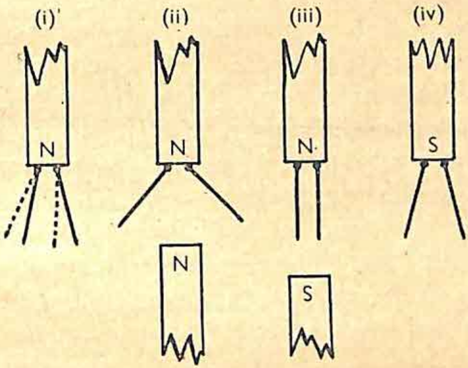


FIG. 180. Magnetic induction.

The two nails are said to have been *magnetized by induction*.†
Now bring up first a N-pole and then a S-pole under the two hanging nails (see Fig. 180 (ii) and (iii)).

What happens? ....

What is the polarity* of the free ends of the hanging nails?....

....

(ii) Repeat the last experiment with the nails hanging from the S-pole of the bar-magnet (see Fig. 180 (iv)).

(iii) Repeat Expt. (iv) on p. 257 with a *soft iron* rod, e.g. a straight piece of galvanized iron wire. Notice that the soft iron does not remain magnetized when it is no longer near a magnet. Hold the piece of un-magnetized soft iron so that its lower end is near

some iron filings. Now place one end of a bar-magnet touching the upper end of the soft iron.

What happens? ....

Remove the bar-magnet. What happens? ....

....

Magnetism produced in a piece of iron when a magnet is brought near it is called *induced* magnetism*, and the iron is said to have become *magnetized by induction.*

Notice the difference between the magnetic behaviour of *soft iron* (i.e. almost pure iron, containing only traces of carbon and other impurities) and that of *steel* (i.e. iron containing 0·5 to 1·5 per cent. carbon). Soft iron readily becomes a strong *temporary magnet* while under the influence of a neighbouring magnet, but loses nearly all its magnetism when the permanent magnet is removed. Steel does not become magnetized by induction as readily as soft iron, but steel retains most of its induced magnetism after the permanent magnet has been removed. The harder the steel, the harder it is to magnetize but the better it retains its magnetism; and the softer the iron, the easier it is to magnetize but the more quickly it loses its magnetism. Permanent magnets, therefore, are made of *steel* or of special alloys.*

THE NATURE OF MAGNETISM

Half fill a long narrow test-tube with *steel* filings and cork it up. Roll the tube on the bench until the filings form a continuous layer from end to end of the tube. Bring one end of the tube near each end of the pivoted bar-magnet or compass needle in turn.

What happens? ....

Lay the tube on the bench and stroke it with a bar-magnet as in Experiment (iv) on p. 257. Now hold each end in turn near the N-pole of the pivoted bar-magnet or compass needle.

What happens? ....

Shake up the iron filings and test again.

What happens? ....

The last experiment suggests that magnetism has something to do with the arrangement of the small particles of iron in the magnet. An un-magnetized steel rod is made up of a very large number of small particles—*molecules*—and it is believed that each of these molecules is a tiny magnet. If these tiny magnets are arranged anyhow, then their poles neutralize each other throughout the rod, and the steel is said to be *un-magnetized*. When the steel rod is stroked with one end of a bar-magnet, some of these molecules turn round so that their N-poles all point in the same direction. The rod then behaves as a magnet (see Fig. 181).

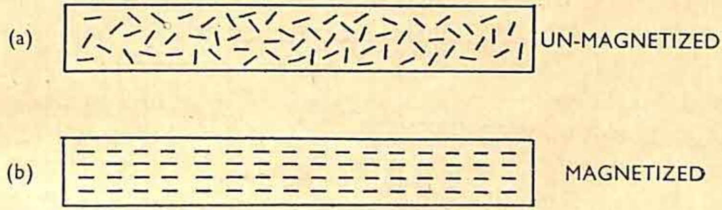


FIG. 181. Diagram to illustrate the molecular theory of magnetism.

In soft iron the molecules can be turned round more easily than in hard steel, hence soft iron is easily magnetized by induction. On the other hand, when the magnetizing force is removed, the molecules in a bar of soft iron readily turn back to their original positions and the iron loses its magnetism. In a hard-steel rod, the molecules are not so easily turned once they have been arranged in their new direction, hence hard steel retains its magnetism better than soft iron.

Anything that disturbs the arrangement of the molecules weakens the magnetism, e.g. if a magnetized steel rod is heated red hot it loses its magnetism, and if a magnet is hammered or dropped its magnetic power is weakened. Magnetize a piece of hack-saw blade and then break it in half. Test the two ends of each half with a pivoted bar-magnet or compass needle.

What do you find? ....

Can you explain this? ....

The space round a magnet, in which the force of the magnet is felt, is called the *magnetic field*† or the *field of magnetic force*. This magnetic field can be mapped out in *lines of magnetic force*, along which the magnetic force acts. *A line of magnetic force is the path along which an isolated* N-pole would travel if it were free to move.* The *direction of the magnetic force* at any point is the direction in

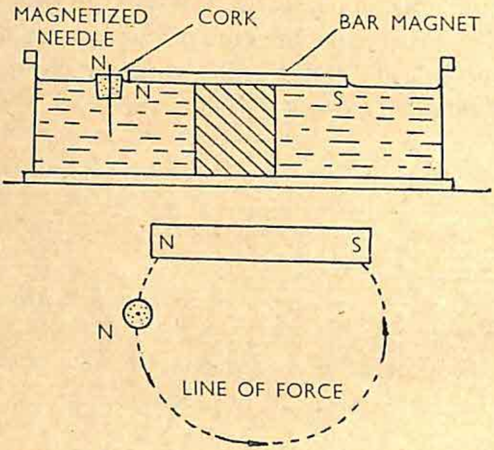


FIG. 182. A floating N-pole moving along a line of force.

which a free N-pole would travel if placed at that point. The following experiment illustrates this:

Take a short piece of magnetized steel wire (or a magnetized needle) and stick it through a small piece of cork so that it floats in a dish of water with its N-pole just above the surface. Support a bar-magnet in a horizontal position, *just above* the water, with its N-pole near the N-pole of the floating magnet. Notice that the floating magnet is repelled and moves slowly along a curved path to the S-pole of the bar-magnet, *tracing out a line of force* (see Fig. 182).

The easiest way of showing the lines of force in a magnetic field is by sprinkling* iron filings on a sheet of paper placed over the

magnet. Each little filing becomes a magnet (by induction) and sets itself in the direction of a line of force.

TO MAP THE LINES OF FORCE IN SOME MAGNETIC FIELDS

(i) (*a*) Fix a cylindrical bar-magnet with its N-pole uppermost in a vertical position (e.g. in a hole in a wood block)[1] and place a sheet of paper on top. Sprinkle a thin layer of iron filings over the paper and notice how the filings arrange themselves in a definite pattern

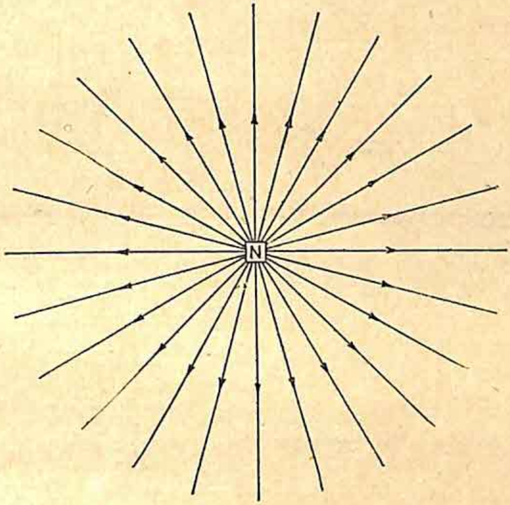


FIG. 183. Lines of force around a single N-pole.

along the lines of magnetic force. Draw a simple map of the magnetic field obtained, marking the direction of the magnetic force along the lines of force (see Fig. 183). (*b*) Repeat the experiment with the magnet reversed, i.e. with its S-pole uppermost.

[1] TEACHERS' NOTE.—A very useful aid for these magnetic experiments is a wood block (5 in. by 4 in. by 2 in.) with two longitudinal grooves, 1 in. apart, cut in one of the larger faces, and with two holes, 1 in. apart, bored through the thickness of the block, to take the cylindrical bar-magnets when making magnetic maps with iron filings. Another hole takes the handle of the dissecting-needle used for pivoting the swinging bar-magnet.

(ii) (*a*) Fix two bar-magnets in a vertical position with their ends 1 inch apart and unlike poles uppermost. Place a piece of paper on top and sprinkle a thin layer of iron filings on the paper as before. Draw a map of the magnetic field round *two unlike poles* (see Fig. 184 (*b*)).

(*b*) Repeat the experiment after reversing one of the magnets, and draw a map of the magnetic field round *two like poles* (see Fig. 184 (*a*)). In this case, also mark the *neutral point* where one pole neutralizes the other so that there is no magnetic force at this spot.

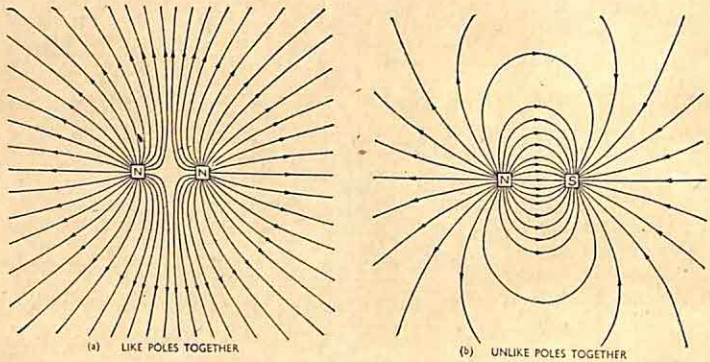


FIG. 184. Lines of force around two neighbouring poles.

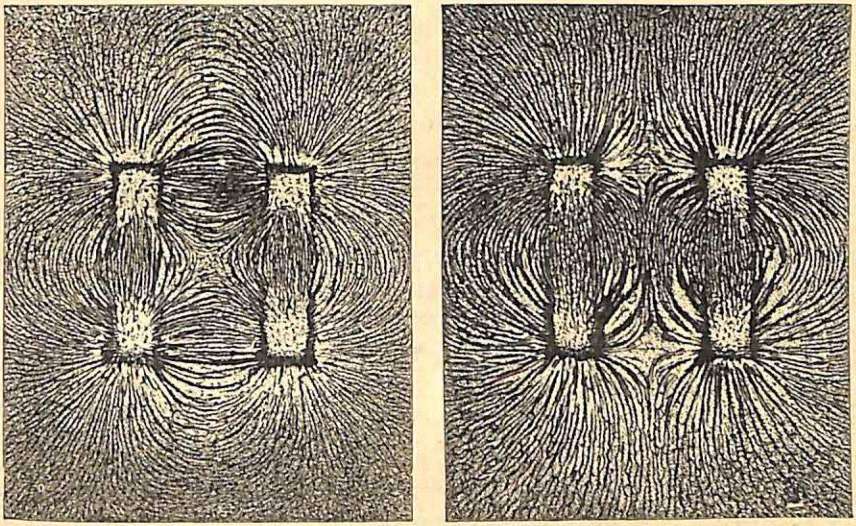
(iii) Place a bar-magnet in a horizontal position (e.g. in a groove in a wood block, or between two thin boards), cover with a piece of paper and sprinkle iron filings over it. Draw a magnetic map of the field of force round a single bar-magnet.

(iv) Place two bar-magnets in a horizontal position, *side by side*, 1 inch apart (e.g. in grooves in a wood block, or with a strip of wood between them) and repeat the experiment. Map the magnetic field round the two bar-magnets (*a*) with their *unlike poles together*, (*b*) with their *like poles together* (see Fig. 185). Mark any neutral points.

(v) Repeat the experiment with two bar-magnets *in line* with each other, and with their ends 1 inch apart. Map the magnetic field

round the two bar-magnets (*a*) with their unlike poles together, (*b*) with their like poles together. Mark any neutral points.

(vi) (*a*) Repeat the experiment with a bar-magnet in line with a short soft-iron rod, and with their ends touching. Notice how the lines of force run through the soft iron and come out of the other end, i.e. the soft-iron rod has become a magnet by induction. Map the magnetic field.



(*a*) (*b*)

FIG. 185. Lines of force around two neighbouring bar-magnets. (*a*) Two bar-magnets with unlike poles together. (*b*) Two bar-magnets with like poles together.

(*b*) Repeat the experiment with the soft-ron rod only. Notice that the filings do not form a pattern, i.e. there are no lines of force because the soft iron has lost its induced magnetism.

THE EARTH'S MAGNETISM

At most points on the Earth's surface, pivoted magnets always set themselves pointing North and South because the Earth itself behaves like a magnet, having its *Magnetic Poles* near the North

and South Geographic Poles. The N-Magnetic Pole is in the North of Canada (in latitude 70° N. and longitude* 97° W.), while the S-Magnetic Pole is in South Victoria Land, in the Antarctic Circle (in latitude 72° S. and longitude 155° E.). Find the Magnetic Poles on a map in your atlas.*

MAGNETIC DECLINATION

Since the Magnetic Poles and the Geographic Poles are some distance apart, a *magnetic compass*, in most parts of the world, does not point '*true north*', and *the angle that the compass needle makes with the* '*true*' (geographic) *north is called the magnetic declination*† at that place. The magnetic declination varies in different parts of the world. Thus in London it is about 14° W. (i.e. a compass needle points 14 degrees West of North); in California, U.S.A., it is about 18° E., while in Malaya the magnetic compass points almost true north (i.e. a *magnetic meridian* runs through Malaya) (see Fig. 186). Magnetic declination also varies from year to year. Because of these differences of magnetic declination from place to place and its *variation* from time to time, accurate *magnetic maps* are prepared for the use of sailors and airmen.

MAGNETIC DIP

If a magnet is free to swing *in every direction*, it will come to rest pointing in the direction of the nearest Magnetic Pole. For example, in the Southern hemisphere such a magnet will come to rest with its S-pole lower than its N-pole, i.e. the magnet will *dip* downwards at one end according to its position on the Earth's surface. At the N-Magnetic Pole such a freely suspended magnet will point with its N-pole *vertically downwards*, while at the S-Magnetic Pole its N-pole will point *vertically upwards*. At places approximately half-way between the Magnetic Poles, i.e. on the Magnetic Equator,† the freely suspended magnet or *dip needle* will take up a horizontal position. The *angle of dip* (see Fig. 186), which is usually measured with a *dip circle* (see Fig. 187), varies therefore between 0° and 90°. For example, in London, the dip needle makes an angle of about

67° with the horizontal, in a northerly direction; in Melbourne, Australia, the angle of dip is about 68° S.; while places in Malaya

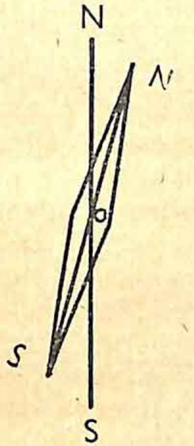


FIG. 186. Diagram illustrating magnetic declination.

NS = geographic meridian. *NS* = magnetic meridian. NO*N* = angle of magnetic declination (approximately 9° E. of N. in this case).

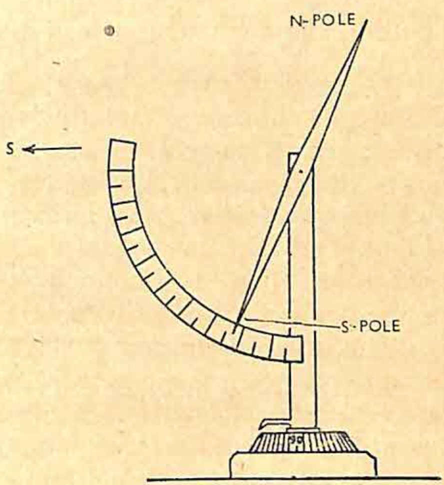


FIG. 187. A simple dip-circle.

are near the Magnetic Equator and the angle of dip is approximately zero.

THE EARTH'S MAGNETIC FIELD

In Fig. 188 are shown the relative positions taken up by a dip needle at various points on the Earth's surface. The lines represent part of the Earth's magnetic field of force. The Earth seems to be a large spherical magnet with a S-seeking pole at what we call the 'N-Magnetic Pole', and with a N-seeking pole at the 'S-Magnetic Pole'.

We have seen that a piece of iron or steel placed near a permanent magnet becomes magnetized by induction. In the same way, since the Earth is a magnet, all iron or steel on its surface

becomes more or less magnetized by its induction, particularly if the iron is placed lengthwise in a north and south direction. Hammering the iron magnetizes it more quickly, since the vibration 'shakes up the molecules' and enables them to turn north and south. If an un-magnetized iron rod is held in a horizontal position

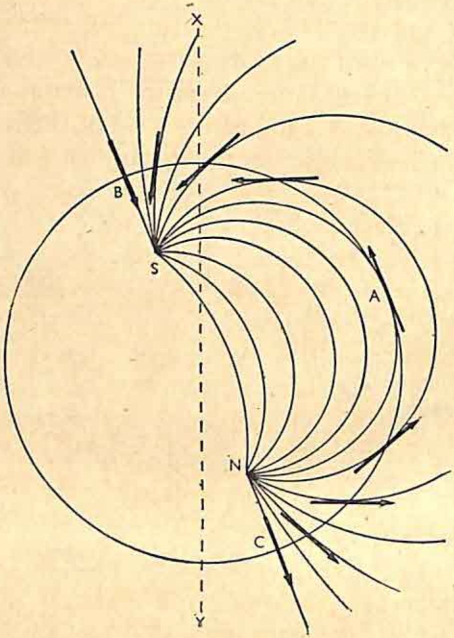


FIG. 183. The Earth's Magnetism.

A—a point of no dip (on the Magnetic Equator). B—a point of maximum dip (at the North Magnetic Pole). C—a point of maximum dip (at the South Magnetic Pole). NS—the Earth's magnetic axis. The vertical line XY represents the Earth's axis of rotation, i.e. the geographic axis. The black arrows show the positions of rest of freely suspended magnets at different points on the Earth's surface.

pointing north and south and one end is struck several times with a hammer, it becomes a magnet. After being dropped *anyhow* on a hard floor for a few times it becomes de-magnetized once more.

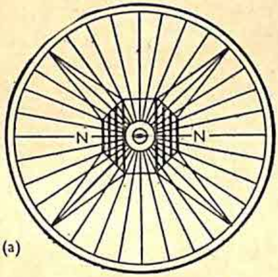
Steel ships that have been built in a north and south position in the shipyard, or which have been sailing on a north and south course for some time in a rough sea, also become strongly mag-

netized by induction, thus causing *deviation** of the ship's compass. In the same way the steel beams running north and south in a steel-framed building soon become magnetized by induction, particularly if the building is exposed to vibration.

MAGNETIC COMPASSES

The Pocket Compass. This is the simplest type of compass. A magnetized strip of hard steel forms the *needle*, and this is pivoted at its mid-point so that it is free to swing horizontally. The *points of the compass* are marked round the case of the instrument.

The Ship's Compass. The older pattern of magnetic compass used



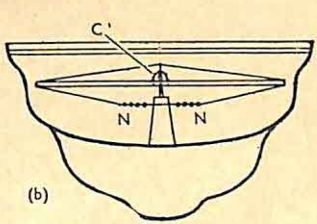


FIG. 189. Ship's compass.
(*a*) = Plan. (*b*) = Vertical section. NN = magnetized needles.

on ships consists of a light, circular disc with several magnetized steel needles fastened side by side to its under surface. The disc is carefully balanced at its centre on a sharp point. The top of the disc is marked with the points of the compass and also in degrees (see Fig. 189). In this older pattern, the whole instrument was supported by two pairs of pivots at right-angles to each other, so that the compass-card always remained horizontal whatever the movement of the ship (see Fig. 190). More modern ships' compasses have the compass-card fastened on a float in a bowl of liquid, so that the card is always horizontal and comes to rest quickly after each change in the ship's direction (see Fig. 191).

Since steel ships become magnetized by the Earth's induction, care has to be taken that this does not cause *deviation* of the ship's

compass and upset the steering of the ship. Permanent magnets are usually placed beneath the compass, at right-angles to each other,

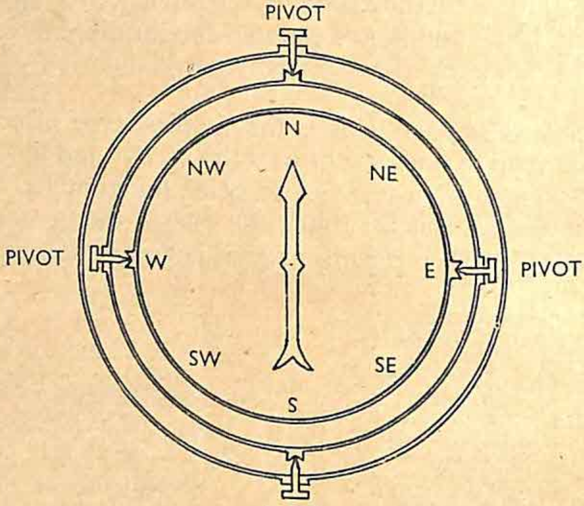


FIG. 190. Method of suspending ship's compass.

and large balls of soft iron are placed on each side of it in order to neutralize the induced magnetism of the vessel (see Fig. 191).

ELECTRO-MAGNETS

Magnetism and electricity are two very closely related forms of energy, in fact, it is impossible to separate one completely from the other. Electric currents have a magnetic effect and magnets can be used to produce electric currents (as we shall see in Book Four).

(i) Set up the apparatus shown in Fig. 192, where A is a pocket-lamp battery, B is a pocket-lamp bulb, C is a pocket-compass standing on a copper wire that runs North and South, and D is a tapping switch. Press the tapping-switch D for a moment and notice the movement of the compass-needle when the current is switched on or off. This shows that *there is a magnetic field round a wire carrying an electric current*. Now reverse the battery connections

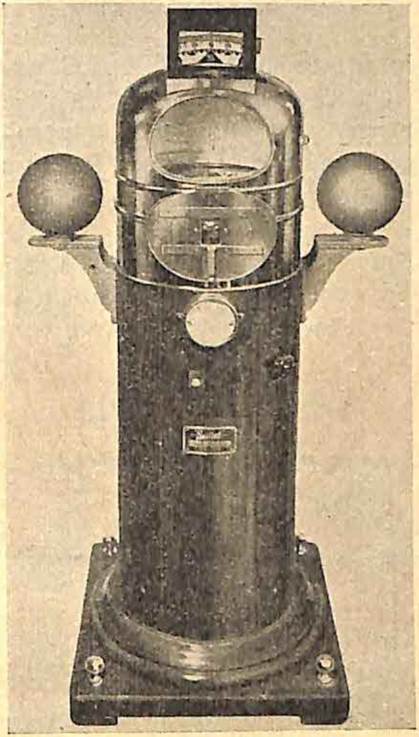


FIG. 191. Ship's compass showing balls of soft iron to neutralize induced magnetism.

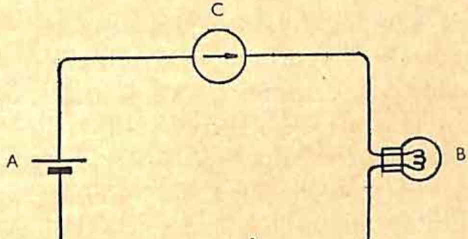


FIG. 192. Magnetic effect of electric current through straight conductor.

and repeat the experiment. The compass-needle 'kicks' in the opposite direction.

(ii) Set up the apparatus shown in Fig. 193, where A is a pocket-lamp battery, B a pocket-lamp bulb, C a hollow spiral coil of cotton-covered copper wire, and D a tapping-switch. Hold a pocket-compass near one end of the coil C and press the tapping-key for a moment. Notice the 'kick' of the needle when the current is switched on or off. Now hold the compass near the other end of the coil C and press the tapping-switch again. Notice that the compass-needle moves in the opposite direction. Hence, *a hollow coil of wire carrying a current behaves like a bar-magnet.*

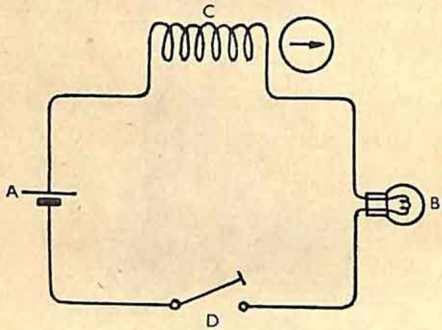


FIG. 193. Magnetic effect of electric current through spiral coil.

(iii) Repeat Experiment (ii) after putting a soft-iron rod inside the wire coil. Notice that the movement of the compass-needle is much greater than before. Also notice that the soft-iron '*core*'* loses its magnetism as soon as the current is switched off.

Hence an *electro-magnet* is easily made by winding many turns of covered copper wire round a soft-iron rod and connecting the ends of the wire to a battery or other source of current. Such electro-magnets can be made very much stronger than any permanent steel magnets, and since they lose their magnetism immediately the current is switched off they are very useful in electrical machines.

Permanent magnets are made by putting bars of *steel* inside coils

of many thousands of turns of wire and passing a strong current round the coil.

Permanent magnets are sometimes made in the shape of a horseshoe. This brings the N-pole and S-pole close together and there is a very strong magnetic field across the poles. Small electromagnets are often made in this shape by wrapping coils of wire round a 'U'-shaped soft-iron core as shown in Fig. 196. Notice that the wire is wound *clockwise** round one side of the 'U' and *anti-clockwise* round the other side, so as to produce opposite poles (i.e. if the 'U' were straightened out, the coil would be continuous and the soft-iron core would become a straight bar-magnet).

EVERYDAY USES OF ELECTRO-MAGNETS

Lifting magnets are used in iron- and steel-works for picking up heavy masses of iron and steel, e.g. pig-iron,* scrap-iron,* steel beams and plates, etc., without having to tie the load to the hook

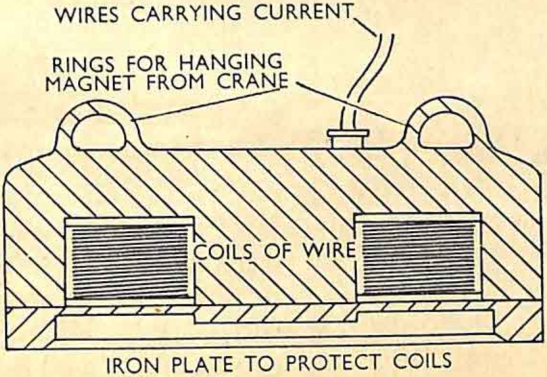


FIG. 194. Section through circular lifting-magnet.

of a crane. The lifting-magnet is hung from a crane in place of the usual hook, and is lowered until it touches the metal that is to be lifted. When the current is switched on, the iron sticks to the magnet and can be lifted and moved as required, and it can then be

released by switching off the current. Such lifting-magnets are usually circular in shape, as shown in Fig. 194, so that more lines of force pass through the article to be picked up. Lifting-magnets of this type are often made several feet in diameter and can lift several tons of iron at a time (see Fig. 195).

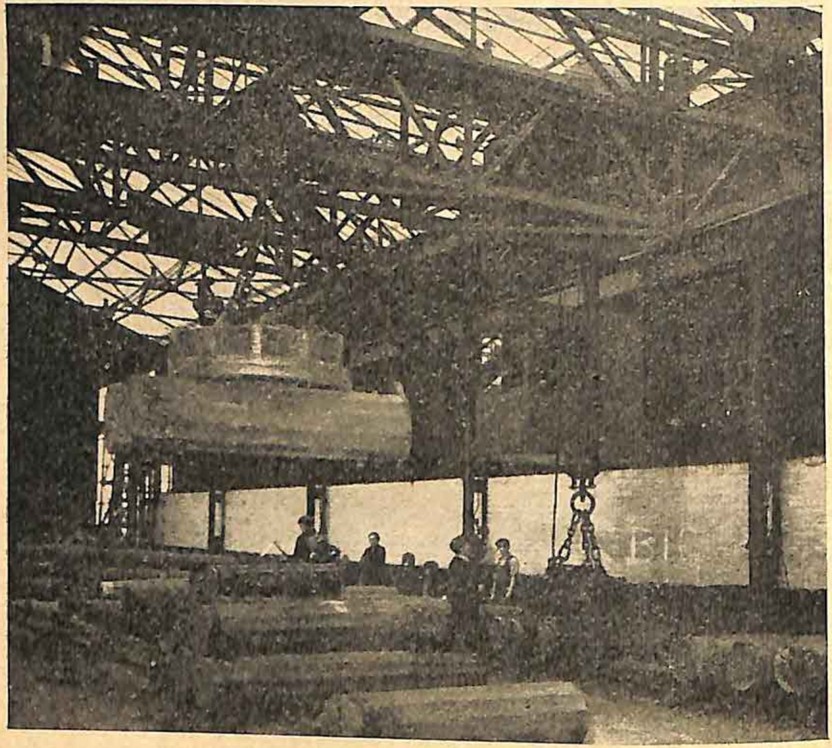


FIG. 195. Industrial lifting magnet.

Electro-magnets are also used in some mining processes for separating magnetic ores from non-magnetic materials. In many industries, too, it is necessary to remove small particles of iron from the materials used, e.g. from the clay used for making pottery, and from foodstuffs that have been ground up between iron rollers.

In hospitals, bits of iron or steel are sometimes removed from people's eyes by the use of a special type of electro-magnet.

ELECTRIC BELLS

Electric bells are a common example of the use of electro-magnets for 'making' and 'breaking' electric circuits. In Fig 196, A and B are the coils of a small electro-magnet with a 'U'-shaped soft-iron core. A steel spring S holds a piece of soft iron C across the poles of the electro-magnet, and the screw D is adjusted until its point just makes contact with S. When the *bell-push* E is pressed, the current flows round the coils A and B, then into the spring S, and out through the contact-screw D back to the battery. When the current flows through the coils, the soft-iron core is magnetized and attracts the piece of soft-iron C, thus making the hammer F strike the bell G. At the same time, S is drawn away from the contact-screw D, so the circuit is broken and the current stops. The soft-iron core of the electro-magnet at once loses its magnetism, releasing C, so that the spring S flies back and makes contact with D once more. This 'makes' the circuit and the current flows again, so that the whole process of '*make-and-break*' is repeated for as long as the bell-push is pressed.

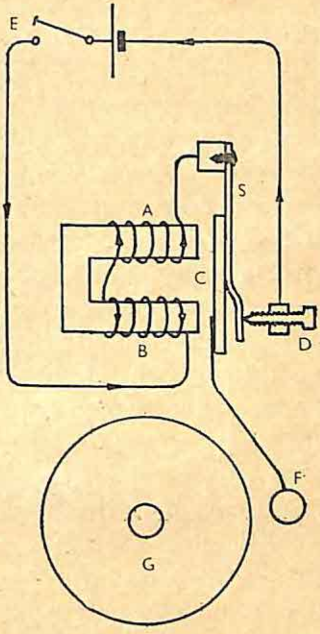


FIG. 196. Electric bell (diagrammatic).

Appendix

PRACTICAL WORK ON ANIMALS

HOW TO USE THE MICROSCOPE

The microscope is a very delicate instrument and must always be handled very carefully.

The microscope enables us to see objects that are too small to be examined otherwise, and to study details of structure which would otherwise be quite unknown. As we learnt on pp. 240–241, a *compound microscope* has a convex lens of short focal length (the *objective*) placed slightly beyond its focal length from the object. This forms a real, magnified and inverted image, which is viewed through another convex lens (the *eyepiece*), used as a magnifying-glass, giving a virtual, magnified, and still inverted image. These two lenses are fixed at either end of the *tube*: the objective at the lower end and the eyepiece at the upper. The tube is supported on a heavy, rigid *stand*, from which projects the *stage* supporting the object to be examined. Beneath the stage is the *mirror*, which reflects a beam of light through the *condenser*, the object (mounted on a glass slide), the objective and the eyepiece in turn. On the stand are *coarse* and *fine screw adjustments* for raising and lowering the tube in focusing (see Fig. 197). The material to be examined is mounted on a glass *slide*, usually 3 in. by 1 in., and is covered with a very thin *cover-glass*, about 0·5 in. in diameter. *Both slide and cover-glass must be perfectly clean. The stage must be kept perfectly dry and clean. On no account may the lenses be touched by the fingers.*

Considerable practice and skill are required before objects can be prepared and mounted on slides, hence it will be best to start with a few objects that require little preparation.

Place a drop of water in the middle of a clean slide and mount in it a few threads of *Spirogyra* (see p. 136). Gently lower a clean

cover-glass on to the drop of water, first letting it come in contact with the slide at one point only, and then lowering the other side

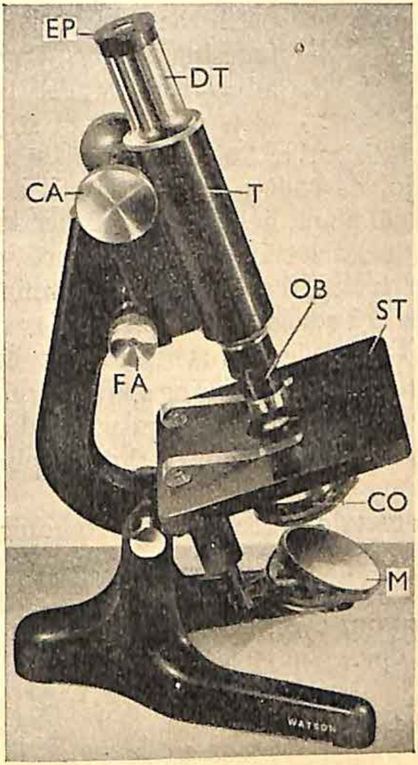


FIG. 197. A microscope.

EP = eyepiece. DT = draw-tube. T = fixed tube. CA = coarse adjustment. FA = fine adjustment. ST = stage. OB = objective. CO = condenser. M = mirror.

by means of a needle or forceps as shown in Fig. 198. Be careful not to trap any air-bubbles. The drop of water should spread out so as just to fill the space under the cover-glass, but it should not spread beyond it. Now place the slide on the stage of the microscope, raising the *low-power* objective about half an inch above the object, and adjust the mirror until a bright circle of light can be

seen through the eyepiece. Then, looking through the eyepiece and using the coarse-adjustment wheel, move the tube *away from the slide* until the object is in focus. After focusing in this way, turn the fine-adjustment wheel to get a clearer view of details of structure.

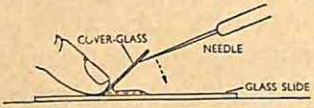


FIG. 198. How to lower the cover-glass.

Notice that each thread of Spirogyra is made up of a number of cylindrical *cells*, joined end to end. Each cell is a complete self-contained individual plant, living quite independently of its neighbours on either side. Each cell has a cellulose *cell-wall* with a slimy covering outside. Inside the cell-wall is a lining of *protoplasm* enclosing a large cell-space with a *nucleus* suspended in it by threads of protoplasm. There is at least one spiral green band in each cell, a flat green ribbon winding spirally from one end of the cell to the other. Embedded in this green band are a number of bright dots where starch, formed during photo-synthesis, is stored.

You are almost certain to see some microscopic, free-swimming plants and animals crossing your field of view. We shall study some of them later.

To avoid tiring your eyes, learn to keep both eyes open when using the microscope.

THE SLIPPER ANIMAL—PARAMECIUM

When dead vegetable matter (e.g. dried grass cuttings) is allowed to stand in water, it begins to *decay* owing to the action of *bacteria*, and in a short time these bacteria multiply so rapidly that they make the water cloudy and may even form a film on the surface. Tiny one-celled animals then appear in the water, feeding mainly on the bacteria.

One of the largest and commonest of these one-celled animals is the '*Slipper Animal*', or *Paramecium* (see Fig. 86). It is about one-

hundredth of an inch in length and can just be seen by the unaided eye, swimming through the water. Put a drop of water containing Paramecium on a microscope slide, together with a few fibres of cottonwool so as to stop the animal from swimming about too quickly, under a cover-glass. Examine under the low power of the

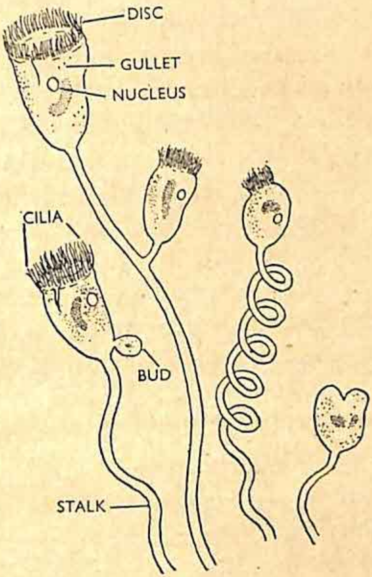


FIG. 199. The Bell Animal—Vorticella (magnified).

microscope, and notice that the animal has a definite shape, like the under side of a slipper, hence the name Slipper Animal. It has a definite shape because the thin outer layer of protoplasm forms a firm membrane. Delicate threads of protoplasm (*cilia*)† project from this firm outer layer, and as these cilia strike the water the animal swims along. Since the cilia are arranged in rows running spirally, Paramecium swims with a peculiar rolling, 'corkscrew' motion. Notice that there is a groove on one side, leading to a funnel-shaped opening into the softer protoplasm

underlying the firm outer membrane. Food-particles are swept into this '*gullet*' and enter the protoplasm, enclosed in a drop of water. Owing to the streaming of the protoplasm, these food-particles circulate round the animal's body while *digestion* takes place, and finally the indigestible residue is got rid of from the body at a point near one end of the groove (the *temporary anus*). Make a drawing of what you see, and label the parts.

THE BELL ANIMAL—VORTICELLA

Another common one-celled animal, the Bell Animal† or *Vorticella*,† is found attached to the stems of water-plants in an aquarium. Mount a drop of water containing Vorticella on a microscope slide under a cover-glass, and examine it under the low power of the microscope (see Fig. 199). Notice that the animal is shaped like a bell with a long, flexible stalk. You may also see a young Vorticella without any stalk, swimming freely through the water before attaching itself to a support. Notice that the 'bell' or body is partly closed by a disc and has a ring of *cilia* round the mouth of the bell. These cilia beat the water so as to form a tiny whirl-pool* (the Latin word *vortex* means 'whirl-pool', hence the name Vorticella). Particles of food are thus swept into the funnel-shaped '*gullet*' and so into the protoplasm as in Paramecium. Notice that, when disturbed, the stalk suddenly coils up into a spiral like a corkscrew, the cilia are withdrawn and the edge of the bell-mouth closes over the disc, thus closing up the animal's body completely. After a time the stalk lengthens again, the bell opens, and the animal goes on feeding again. Make a drawing of what you see, labelling the parts.

THE FROG

Examine a living frog under a bell-jar, and watch the breathing movements of the floor of its mouth.

EXTERNAL CHARACTERISTICS OF FROG

Before beginning to dissect your frog (which has been killed painlessly with chloroform†) examine the following features:—

Notice (*a*) the division of the body into *head*, *trunk*, *fore-limbs*, and *hind-limbs* (no neck and no tail), (*b*) the damp, smooth, loose-fitting *skin* (dry and rough in toads), (*c*) the flat, broad *head* with a large, slit-like *mouth*, a pair of *nostrils*, a pair of projecting *eyes* with eyelids, and a pair of circular *ear-drums*.

Pay special attention to the inside of the *mouth-cavity*. Notice (*a*) the wide gape* of the semi-circular *jaws*, (*b*) the single row of fine *teeth* along the upper jaw (absent in toads), (*c*) the *internal opening to the nostrils*, (*d*) the *inner surface of the eyeballs*: press the eyeballs gently from the outside and notice how they project into the mouth-cavity, (*e*) the *inner openings to the tubes leading to the ears*, (*f*) the *glottis*,† a slit-like opening, leading to the *lungs*: this is kept closed when the frog swallows food, (*g*) the *opening to the gullet*, (*h*) the long *tongue*, attached to the front of the floor of the mouth and divided into two at its free, backward-pointing end (see Fig. 104).

Notice the opening to the *cloaca*, which forms the posterior end of the food-canal, into which open also the kidney-ducts and the reproductive ducts.

DISSECTION OF FROG

Pin out the frog on its back in a dissecting-dish and just cover the animal with water (or, better, with 0·6 per cent. common salt solution).[1]

(i) Turn back the *skin* from the ventral surface of the body, as follows: Pinch up the skin about the middle of the belly with a pair of forceps and make a small cut with the scissors (see Fig. 200 (1)). Then cut through the loose-fitting *skin* along the middle line, forwards to the lower jaw and backwards to near the cloaca. Then cut the skin along each upper arm and thigh, turn the pieces of skin outwards and pin them down (see Fig. 200 (2)). The skin is very

[1] Using a salt solution of the same concentration as the frog's body-fluids keeps the various organs at their normal size by preventing swelling due to osmosis.

easily removed because of the large *lymph-spaces* underlying it. Notice the blood-vessels of the skin, which assist in external respiration. Notice, too, the *muscles* of the limbs and body-wall.

(ii) Open up the *body-cavity* as follows: First notice the position of the vein running along the mid-line of the ventral body-wall, so that you can avoid cutting it accidentally later. Then pinch up the

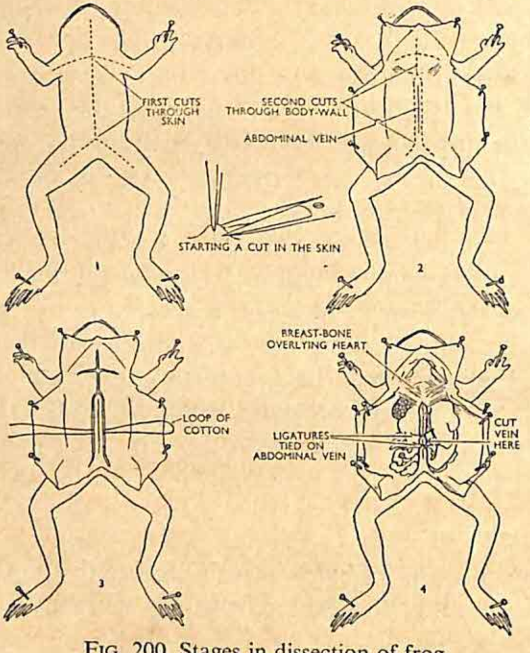


FIG. 200. Stages in dissection of frog.

muscular body-wall a little to one side of this vein and make a cut with the scissors. Make a second cut on the other side of the vein and ligature* the vein by tying thread round it at two points about a quarter of an inch apart (see Fig. 200(3)). The vein can then be cut between the ligatures without loss of blood. Now continue the two cuts on either side of this vein forwards to the *shoulder-girdle* and backwards to the *hip-girdle*. With the large scissors, carefully cut through the shoulder-girdle at two points a little to the right and

left of the middle-line; then cut across the *breastbone* so as to leave the ligatured vein behind, leading to the liver. Now pin back the body-wall to expose the internal organs (see Fig. 200 (4)).

Notice (*a*) the *heart*, enclosed in a thin membrane (the *heart-sac*). Pinch up this thin membrane with fine forceps and cut it away very carefully with fine scissors. (Although the frog is quite dead, as you touch the heart in removing the heart-sac, and when it comes in contact with the water or salt solution, it will probably start beating again. This does not mean that the frog is coming to life again: heart muscle has the property of continuing to contract and relax *automatically*, without nervous control, even after removal from the body.)

Notice (*b*) the *liver*, a large, reddish-brown organ, with the green *gall-bladder* lying between its two halves, (*c*) the *lungs*, thin-walled, transparent pink sacs, often blown out with air if the glottis has not been opened, (*d*) the *stomach*, a wide, curved tube, (*e*) the *small intestine*, a narrow, coiled tube, with (*f*) the *pancreas*, a pink, irregularly-shaped gland lying between the stomach and the first part of the small intestine, (*g*) the *spleen*, a small, round, dark-red body lying in the middle of the body-cavity between the small and large intestines, (*h*) the *large intestine*, a short, wide tube leading to (*i*) the *cloaca*, a chamber into which open also the excretory and reproductive ducts, and (*j*) the *bladder*, a very thin-walled sac, situated at the hinder end of the body-cavity (see Fig. 201). Notice, too, that the stomach and intestine are supported by a transparent fold of membrane (the *mesentery*) with a network of blood-vessels running through it.

(iii) Having identified all the parts of the food-canal and made a drawing of what you see, remove the food-canal by cutting carefully across the gullet, through the transparent mesentery, and across the large intestine just above the cloaca. This will expose the *kidneys* and the *reproductive organs*. The *kidneys* are dark-red, flattened, oval bodies, with small yellow patches—the *adrenal*† *glands*—on their surface. Near the kidneys are two yellow or orange-coloured organs—the *fat bodies*, containing reserve food

material. In the *male frog*, look for the *testes*,† a pair of pale yellow, oval bodies overlying the kidneys, producing *sperms* that pass through the kidney and down the *kidney-duct* to the cloaca. In the *female frog*, the reproductive organs are more readily seen, especially when filled with *eggs*. Notice (*a*) the *ovaries*, two large,

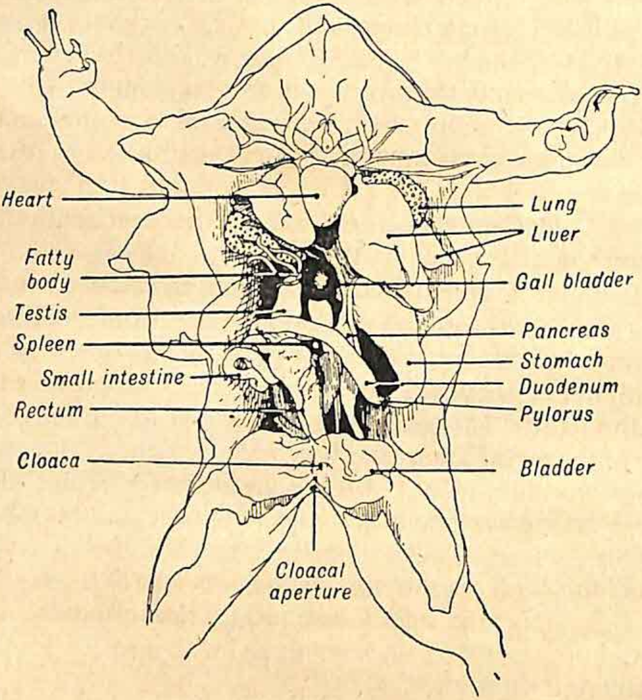


FIG. 201. General dissection of male frog.

irregularly-shaped bodies, containing a mass of black and white egg-cells, (*b*) the *oviducts*,† coiled tubes that convey the egg-cells to the cloaca.

(iv) Notice that the frog's *heart* has *three chambers*: one thick-walled muscular *ventricle* and two thin-walled, darker-coloured *auricles*. Carefully turn the heart forwards and upwards and

examine on its dorsal side (*a*) the triangular, thin-walled sac formed by the union of the three main veins from the body; (*b*) the large vein formed by the union of the veins from the right and left lungs, entering the *left auricle*. Now examine the ventral side of the heart and notice the *main artery* arising from the *ventricle* and dividing into two main branches. Each branch divides into *three arteries*, sending blood (1) to the lungs and skin, (2) to the trunk and limbs, and (3) to the head.

(v) Very carefully remove the heart, lungs, liver, kidneys, and reproductive organs, and then notice (*a*) the *backbone*, and (*b*) the *spinal nerves*, ten in all, emerging from the spinal cord between the joints of the backbone. The 7th, 8th, 9th, and 10th spinal nerves, supplying the leg-muscles, run close together and are more readily seen than the others.

(vi) Examine a prepared frog *skeleton* and notice (*a*) the *skull* with its bony cases for the brain and the organs of smell and hearing, (*b*) the *backbone* consisting of nine jointed vertebrae and one long, unjointed bone, (*c*) the *shoulder-girdle* supporting the *fore-limbs*, and (*d*) the *hip-girdle*, firmly attached to the backbone and supporting the *hind-limbs* (see Fig. 103).

In the fore-limb, identify (*a*) the *upper-arm bone*, (*b*) the *lower-arm bone*, (*c*) the *wrist-bones*, (*d*) the *hand-bones*, and (*e*) the *finger-bones*.

In the hind-limb, identify (*a*) the *thigh-bone*, (*b*) the *leg-bone*, (*c*) the *ankle-bone*, (*d*) the *foot-bones*, and (*e*) the *toe-bones*.

PHERETIMA—THE INDIAN EARTH-WORM

(i) Study the habits of living earth-worms in a 'wormery' that has been set up as follows: A glass vessel, with an opening at the bottom for drainage, has a layer of stones placed in it and is then filled with damp earth, preferably in several layers of differently coloured earth, e.g. black garden soil, red lateritic soil, grey sandy soil. If the 'wormery' is kept covered with a light-tight box, some of the tunnels will be made against the glass where they can be examined.

Notice how the worms mix up the different layers of soil until finally it becomes uniform in colour throughout.

(ii) Examine some living earth-worms kept in a tin fitted with a loosely-fitting cover and containing a layer of damp soil. (*a*) Remove the cover suddenly. You will probably find the worms on the surface. If so, notice how they bury themselves at once, showing that they are *sensitive to light*. (*b*) Replace the cover, and after a long interval repeat the experiment, but first tap the side of the tin before removing the cover. You will most probably find that the worms have already buried themselves, showing that they are *sensitive to vibration*. (This is usually the only warning a worm gets of an approaching* enemy.)

(iii) Place a live worm on a piece of dry brown paper and study its movements. (You may be able to *hear* its walking-movements.) Notice the slimy skin. Also notice how the mouth is alternately pushed out and drawn in. (*a*) Dip the end of a matchstick in a strong-smelling substance, e.g. oil of cloves† or turpentine, and hold it near (but not touching) different parts of the worm. Notice the sensitivity to smell and find out which part of the body is most sensitive. (*b*) Twist a little cotton-wool round the end of a match-stick and dip it in 10 per cent. alcohol. Lightly touch different parts of the worm with the alcohol and notice the response. Find out which part of the worm's body is most sensitive.

(Worms may be killed in an expanded condition for dissection by putting them in chloroform-water or, better, by putting them in a little water and then adding alcohol *gradually* during two hours until there is about 10 per cent. of alcohol present, e.g. 20 c.cm. of water and 2 c.cm. of alcohol. Afterwards, they can be hardened and preserved, if necessary, by pinning out in 5 per cent. formaldehyde† for a day or two and then keeping them in 90 per cent. alcohol.)

EXTERNAL CHARACTERISTICS OF INDIAN EARTH-WORM

Examine an earth-worm that has been killed in an expanded condition and notice, using a hand-lens when necessary, (*a*) the

ring-like *segments*—about 100 in number, (*b*) the *mouth*, (*c*) the *anus*, (*d*) the '*saddle*' covering segments 14, 15, and 16, (*e*) the *dorsal blood-vessel*, showing through the body-wall, (*f*) the *female reproductive opening* on the ventral surface of segment 14—at the anterior end of the 'saddle', (*g*) the two *male reproductive openings* on the ventral surface of segment 18, and (*h*) the ring of *bristles* round the middle of each segment (these are most easily seen near the ends of the worm). Examine these bristles under the microscope on a piece of body-wall that has been treated with sodium hydroxide solution for a few minutes, then washed and mounted in glycerine† (see Fig. 88).

DISSECTION OF INDIAN EARTH-WORM

(i) Pin down the worm in the dissecting-dish *with its dorsal surface upwards*, putting a pair of small pins through the *sides* of segment 4, and another pair near the tail. Cover the worm with water and *carefully* cut through the body-wall at about segment 30 and continue cutting forward along the mid-dorsal line right up to the anterior end (without damaging any of the underlying organs). (Notice the thin, transparent skin, which often comes away from the body at this stage. Mount a small piece of skin in glycerine and examine it under the microscope. Notice the numerous fine, criss-cross grooves that disperse the light and produce a rainbow-coloured effect.) Pin out the body-wall on either side with pairs of small pins through segments 8, 12, 16, and so on.

In pinning out the animal, gently separate the body-wall from the food-canal by breaking through the thin transverse walls between the segments with a seeker* (see Fig. 89).

(ii) Notice (*a*) the *body-cavity* between the food-canal and the body-wall, and identify the following parts of the food-canal: (*b*) the *mouth*, (*c*) the muscular *throat* in segment 4, attached to the body-wall by numerous threads of muscle, (*d*) the *gullet*, extending from segments 4 to 14, with (*e*) the *gizzard*, a rounded muscular organ for grinding up the food, in segment 8, and (*f*) the *intestine* running straight backwards to the anus.

(iii) Notice (*a*) the *dorsal blood-vessel* running along the whole length of the food-canal in the mid-dorsal line, and (*b*) the '*hearts*', blood-vessels branching from the dorsal blood-vessel and forming rings round the gullet in segments 12 and 13.

(iv) Identify the following *reproductive organs*: (*a*) two or three pairs of *sperm receptacles** in segments 6–8 (for storing 'foreign' sperms received from another worm), (*b*) two pairs of *sperm-sacs* in segments 11 and 12 (for storing the worm's own sperms), (*c*) a pair of *prostate*† *glands* in segments 16–20, just behind the 'saddle' (producing a liquid that probably plays some part in reproduction).

(v) Cut across the food-canal just behind the throat and *very carefully* remove the food-canal backwards, without damaging the reproductive organs or the *ventral nerve cord*. (Cut across the gizzard transversely and examine with a hand-lens. Notice the thick, muscular wall and the horny lining.) Notice (*a*) the *ventral nerve cord*, with a *nerve-centre* in each segment, and (*b*) the *nerve-collar* round the food-canal just in front of the throat, and (*c*) the '*brain*', forming the dorsal part of the nerve-collar.

(vi) The two pairs of *testes* are attached to the sperm-sacs in segments 10 and 11, and two pairs of very fine *sperm-ducts* run backwards to the two male reproductive openings in segment 18. There is a pair of tiny *ovaries* in segments 13 and 14, and a pair of very fine *oviducts* lead to the female reproductive opening in segment 14.

THE COCKROACH

Watch living cockroaches in a glass vessel, and notice (*a*) the method of walking—three legs moving at a time, (*b*) the movements of the long *feelers*, (*c*) the breathing movements of the hind-body, (*d*) the movements of the mouth parts in feeding.

EXTERNAL CHARACTERISTICS OF COCKROACH

(i) Examine a cockroach that has been killed by chloroform and notice (*a*) the three distinct body-regions—*head*, *fore-body*, and

hind-body, (*b*) the short, narrow *neck*, (*c*) the *three pairs of legs*, attached to the under side of the fore-body, and (*d*) the *two pairs of wings* on the back of the fore-body. Notice that the whole body is covered by a thick, horny, *external skeleton* (see Figs. 90 and 92).

(ii) Examine the *head* with a hand-lens, and notice (*a*) the large, black, *compound eyes*, (*b*) the long, slender, jointed *feelers*, and (*c*) the three pairs of jointed *mouth parts* for capturing and tearing up the food (see Fig. 91).

(iii) Examine the *fore-body* and notice (*a*) the *three thoracic segments*, covered above and below with horny plates, the first segment (from the head end) bearing a shield-shaped plate extending outwards on all sides and hiding the neck and part of the head, (*b*) the *organs of movement*—three pairs of 5-jointed, clawed *legs*, one pair on each segment, and two pairs of *wings*, on the second and third segments of the fore-body. The first pair of horny *wing-cases* protects the thinner pair of *flight-wings*. Draw (*a*) a walking leg, (*b*) a flight-wing, (*c*) a wing-case.

(iv) Examine the *hind-body*, which is made up of *ten abdominal segments* (although the last few overlap each other and are hard to distinguish). The *anus* is beneath the last segment. Notice the pair of jointed rods on the last segment. In the *male cockroach* there is a second pair of unjointed rods on this segment. These latter are absent in the *female cockroach*, which has a boat-shaped structure on the under side of the hind-body (see Fig. 92). With a hand-lens, look for the *breathing-pores* on either side of the body—two pairs on the fore-body and eight pairs on the hind-body.

DISSECTION OF COCKROACH

(i) Fix the animal in a dissecting-dish with the dorsal side upwards, either with wax or with small pins passing through the *edges* of the fore-body and hind-body. Cut off the wings and then cut away the horny plates covering the dorsal surface of the hind-body and fore-body. *Do this very carefully, without breaking the underlying thin skin*. Notice (*a*) the '*heart*', a long, straight tube running along the mid-dorsal line, divided into thirteen chambers,

one in each segment. (In the cockroach, the blood is not concerned with respiration and is colourless.) (ii) Cut through the thin body-wall and expose the *food-canal*, then carefully separate it from the surrounding *fat body* (see Fig. 93A). Notice (*a*) the *salivary glands* and *salivary receptacle*, (*b*) the narrow *gullet* leading into (*c*) the large, swollen *crop*. Behind the crop is (*d*) the small, muscular *gizzard*, in which the food is ground up by means of a ring of six horny teeth. The gizzard leads into (*e*) the short *mid-gut*, at the anterior end of which are (*f*) seven or eight finger-like *digestive glands* opening into the mid-gut. Then follows (*g*) the *hind-gut*, bearing numerous yellow thread-like *excretory organs*. The posterior end of the hind-gut opens to the exterior by the *anus*.

(iii) Notice the fine, silvery, branching *air-tubes* conveying air from the breathing-pores to every part of the body. Mount some of these air vessels in a drop of glycerine and examine them under the microscope or with the micro-projector.

(iv) Remove the food-canal and fat body and look for the *reproductive organs*. The *testes* in the *male cockroach* are very small and very difficult to find, but the two *ovaries* of the *female* are easily seen as two bunches of eight tubes containing numerous *eggs*.

(v) Look for the double *nerve-cord* running along the mid-ventral line, with a swelling (or *nerve-centre*) in each segment (except the hinder segments), and *branch nerves* leading outwards from these swellings. The dissection of the front end of the nervous system (or '*brain*') is a very delicate operation (see Fig. 93B).

THE SNAIL

A frog is an example of a *Vertebrate*—an animal with an *internal skeleton* of bones, built round a central backbone. *A cockroach* is an example of an *Arthropod*—an animal with a number of *jointed limbs* and with a hard *external skeleton*. A snail is an example of a *Mollusc*—a soft-bodied animal with no skeleton at all, either internal or external, although most molluscs have shells of calcium carbonate to protect their more delicate organs.

EXTERNAL CHARACTERISTICS OF SNAIL

(i) Examine a living snail. Notice (*a*) that the body is not divided into segments; (*b*) that there are no limbs. Notice, too, (*c*) the large, flattened, muscular '*foot*' covered with slime, and watch the waves of muscular contraction passing forwards along the under side of the 'foot' as a snail moves over a sheet of glass; (*d*) the *shell*, a right-handed, conical spiral, enclosing most of the internal organs and into which the animal can withdraw itself for protection; (*e*) the two pairs of '*horns*' on the *head*, which can be pulled back inside the body when the animal is disturbed. The upper pair of horns are longer and bear *eyes* (see Fig. 99).

(ii) Examine a snail that has been killed in an expanded condition by drowning in air-free water, and notice (*a*) the *mouth*, bordered by three lips; (*b*) the opening to the *mucus-gland*, just below the mouth; (*c*) the *reproductive opening* on the right side of the head, just behind a long 'horn'; (*d*) the thick, muscular *collar* surrounding the mouth of the shell; (*e*) the *respiratory opening*, a large opening inside the collar, leading into the *mantle cavity*, which is enclosed by the shell; and (*f*) the *anus*, a small, slit-like opening at the side of the respiratory opening.

DISSECTION OF GIANT SNAIL

(iii) Take a snail that has been killed by drowning and then washed in 50 per cent. alcohol to remove the mucus. Since most of the internal organs are enclosed in the shell, it is first necessary to remove this. The shell can often be twisted away from the animal, without damaging the delicate internal organs, but if you have the slightest difficulty in doing this, you must remove the shell *very carefully*, *bit by bit*, using strong scissors or forceps, starting from the *lip* of the shell (the last-formed part) and working up to the *apex*, which is the oldest part of the shell. Notice (*a*) the *lines of growth*, ridges running parallel to the lip, showing former positions occupied by the lip of the shell during growth, since the shell increases in size as the snail grows.

(*b*) Put a piece of snail-shell in dilute hydrochloric acid and

notice that it dissolves readily, giving off carbon dioxide, and leaving behind only a thin, transparent membrane. (The greater part of the shell consists of calcium carbonate.)

(iv) Pin down the snail in a dissecting-dish, sticking pins firmly through the edge of the 'foot', and cover with water. Examine the coiled part of the snail that was enclosed by the shell, and notice

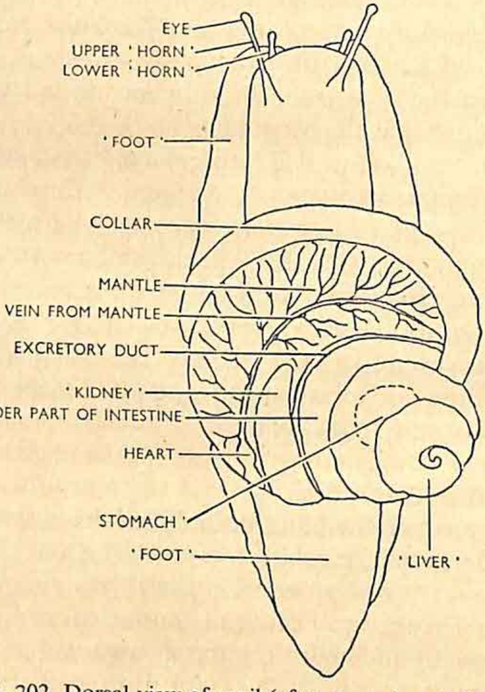


FIG. 202. Dorsal view of snail (after removing shell).

(*a*) the *mantle*, a fold of thin skin, forming the roof of the *mantle-cavity*, with a network of blood-vessels running through it; (*b*) the wide *intestine* running along the right edge of the mantle, with (*c*) the narrow *kidney-duct* alongside, and (*d*) the '*kidney*', a triangular *excretory organ*, and, to one side of the 'kidney', (*e*) the *heart*. (*f*) The *digestive gland* (or '*liver*') fills most of the apex of the shell,

and on its surface can be seen (*g*) one or two turns of the *intestine*, (*h*) part of the surface of the light-coloured '*stomach*', and (*i*) the light-coloured *albumen*†-*gland*, between the two halves of the liver (see Fig. 202).

(v) Starting from near the respiratory opening, cut along the line where the mantle joins the collar, and turn back the roof of the mantle-cavity so as to expose (*a*) the *mantle-cavity*, (*b*) the *heart*, and (*c*) the *excretory organ* (or '*kidney*'). Notice that the mantle is well supplied with blood through a network of blood-vessels. Carefully cut open the *heart-sac*, the thin membrane surrounding the heart, and notice that the heart has *two chambers*, (*a*) a thin-walled *auricle*, and (*b*) a thick-walled, muscular *ventricle*. Cut through the front of the respiratory opening and identify the *anus*. Close by the anus is a still smaller *excretory opening* where the kidney-duct opens to the exterior. Cut through the collar on the other side of the intestine and continue the cut along the mantle so as to free the intestine, which can then be pinned back (see Fig. 203).

(vi) Cut forwards from the front of the collar along the dorsal middle line of the body to the head, and pin out the sides. *Carefully* remove the thin skin from the delicate internal organs and sort out the digestive organs, pinning out the food-canal on the left-hand side of your dissection. Also sort out the reproductive organs and arrange them on the right-hand side of your dissection (see Fig. 203).

FOOD-CANAL OF SNAIL

(vii) Starting from the head end, notice (*a*) the rounded, muscular *throat*, surrounded by (*b*) the *nerve-collar*; (*c*) the narrow, thin-walled *gullet* leading to the large, thin-walled *crop*, on either side of which are (*d*) a pair of white *salivary glands*, each with a *salivary duct* leading forward to the front of the gullet. The crop narrows behind and leads to (*e*) the '*stomach*', a round, thick-walled sac embedded in the '*liver*'. From the 'stomach', (*f*) the *intestine* winds through the 'liver' and runs back to the hinder end of the mantle-cavity, leading to (*g*) the *anus*. Notice, too, (*h*) the '*liver*', a very large brown *digestive gland*, with one part of it filling

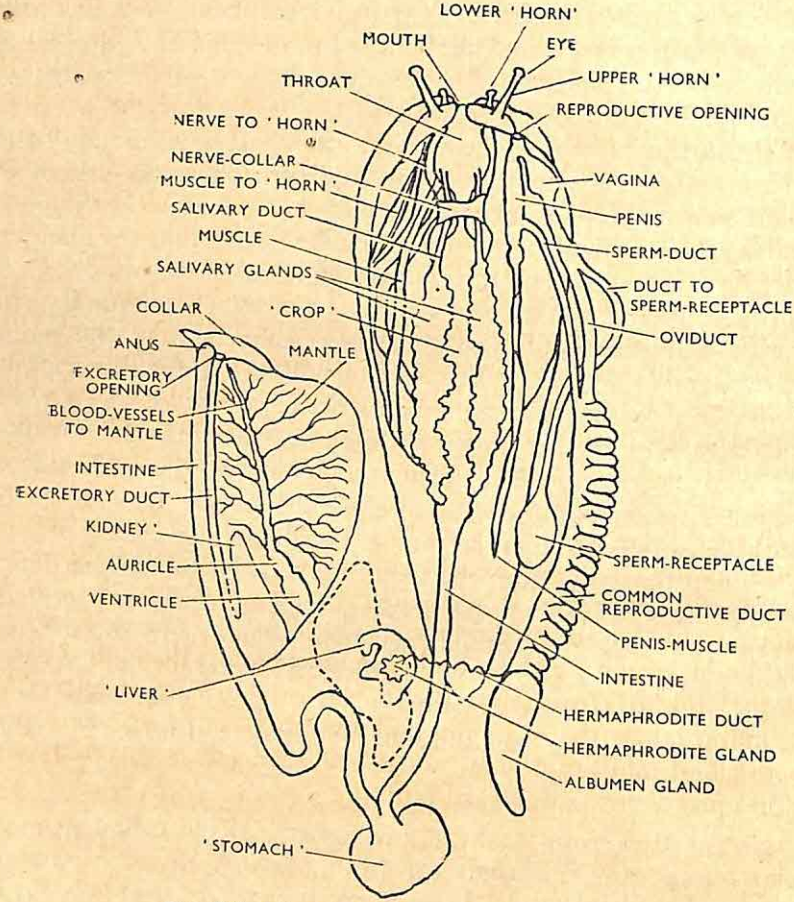


FIG. 203. Dissection of Giant Snail—Achatina.

the apex of the shell above the 'stomach' and albumen-gland; and the other, larger, part lying between the 'stomach' and the mantle-cavity.

REPRODUCTIVE ORGANS OF SNAIL

(viii) The reproductive system is very complicated because a

snail is *bi-sexual* or *hermaphrodite*,* possessing both male and female organs, although it is not self-fertilizing (see Fig. 203).

Notice (*a*) the small *hermaphrodite gland*, embedded in the smaller part of the liver (near the apex of the shell), which produces both *egg-cells* and *sperms*. The egg-cells and sperms, when ripe, pass down (*b*) the wavy, white *hermaphrodite duct* leading to the lower end of (*c*) the *albumen-gland*, from which arises (*d*) the *common reproductive duct*, containing male and female ducts running side by side and then dividing into (*e*) a *female duct* (the *oviduct*) and (*f*) a *male duct* (the *sperm-duct*). The *male duct* leads to (*g*) the *penis*,† a muscular tube, while the female duct leads to (*h*) the *vagina*.† The penis and the vagina then join together and open to the exterior at the *reproductive opening*. From the hinder end of the vagina arises a long tube ending in a sac—the *sperm receptacle*—in which are stored the 'foreign' sperms received from another snail.

(ix) Examine the simple *eyes* at the ends of the longer 'horns' (pushing them out with a seeker if necessary) and notice the *nerves* running to the 'horns' from the nerve-collar, and also the *muscles* that serve to withdraw the 'horns'.

(x) Cut across the gullet and then cut forward through the roof of the throat. Dissect out the '*tongue*' and mount in glycerine. Examine under the low power of the microscope or micro-projector and notice its file-like appearance; it is covered with thousands of tiny, backward-pointing '*teeth*'.

SCOLIODON—THE INDIAN SHARK

The Indian Shark (*Scoliodon*)† is suitable for dissection as an example of a gristly fish, being of convenient size and widely distributed in tropical and sub-tropical seas. A freshly-caught fish is best for dissection, after removing as much mucus as possible by washing under the tap. If really fresh specimens are not available, small sharks preserved in 5 per cent. formaldehyde can be used.

(i) Put the fish on a dissecting-board and notice the smoothly-curved, 'stream-lined'* shape, pointed at both ends, and the flattened head (see Fig. 101). Stroke the skin with your finger, first from head to tail and then in the opposite direction, noticing that the skin feels smooth when stroked backwards and very rough (like a coarse file) when stroked forwards. This is because the whole surface of the skin is covered with backward-pointing *scales*. To see these tiny, pointed projections more clearly, examine the skin with a hand-lens.

Notice that there are two kinds of *fins*, paired and unpaired. These fins are flattened outgrowths of skin supported by a skeleton of gristle. The *paired fins* correspond to the fore-limbs and hind-limbs of other 'higher' backboned animals. The two *fore-fins* are roughly triangular in shape and project from the sides of the ventral surface of the body, just behind the gill-slits. The two *hind-fins* are smaller than the fore-fins and project from the ventral surface of the body midway between the head and the tail. The opening to the *cloaca* is between the hind-fins. In the male shark, the inner edge of each hind-fin bears a grooved, rod-liked *clasper*,† by means of which the sperms are transferred to the oviducts of the female.

There are four *unpaired fins*: (*a*) a large, vertical, triangular *anterior dorsal fin*, a little in front of the middle of the body; (*b*) a much smaller *posterior dorsal fin*, farther back; (*c*) a *tail fin*, extending round the dorsal and ventral surfaces of the end of the tail; and (*d*) a *ventral fin*, between the hind-fins and the tail. Make an outline drawing of the fish in side view, labelling the parts.

(ii) Identify the external openings: (*a*) The wide, curved *mouth*, on the underside of the head. (The shark is a 'bottom feeder'.) Notice that the inner surface of the mouth is covered with backward-pointing scales, which are much enlarged over the jaws to serve as *teeth* (for capturing the prey but not for chewing it). Notice that while it is easy to push your finger into its mouth, the backward-pointing teeth make it difficult to pull the finger out

again without opening the fish's jaws. (*b*) The *nostrils*, a pair of openings leading to the *organs of smell*, on the underside of the head in front of the mouth. (*c*) The *gill-slits*, five vertical slits on each side of the head behind the eyes, through which water escapes after being taken in at the mouth and then passed over the gills. (*d*) The opening to the *cloaca*, between the hind-fins, the external opening to the hinder end of the food-canal, which also receives the excretory ducts, and the reproductive ducts. Draw the underside of the head to show the mouth and nostrils.

Notice the *lateral line*† running along either side of the body, marking the position of the *lateral line canal* just beneath the skin. This tube, which is filled with a transparent, jelly-like material, branches in the head region and opens to the exterior at intervals through tiny pores. After drying the skin of the head with a cloth, press on the skin and squeeze out some of the jelly from these pores. This lateral line system is sensitive to currents and vibrations in the surrounding water.

Notice that there is no clear division into head, trunk, and tail: for convenience, however, the part anterior to the last gill-slit is called the head, the part posterior to the hind-fins is called the tail, and the part in between is called the trunk.

(iii) Lay the fish on its back on the dissecting-board and fasten it down with nails passing through the tail and through the bases of the fore-fins (without stretching the fore-fins too far apart). Carefully open up the body-cavity by cutting through the skin and body-wall along the mid-ventral line with large scissors, forward to the shoulder-girdle and backwards to the hip-girdle. Make transverse cuts through the body-wall just behind the shoulder-girdle and just in front of the hip-girdle, and cut away the side pieces of body-wall between the fore-fins and the hind-fins.

Identify the following organs before proceeding any further: (*a*) The *liver*, a very large, solid organ, divided into two halves extending nearly the full length of the body-cavity. (*b*) The *stomach*, a wide, 'J'-shaped tube, the longer limb of which extends nearly the full length of the body-cavity. (*c*) The *spleen*, a long, narrow organ

attached to the stomach. (*d*) The *pancreas*, a small gland lying in the angle between the two limbs of the 'J'-shaped stomach. (*e*) The *intestine*, a wide, straight tube running backwards from the stomach to the cloaca. In a female fish, the *ovaries* may be seen at this stage of the dissection.

(iv) Dissect out the food-canal by cutting through the supporting transparent membrane. After identifying the various parts, open up the food-canal from end to end by a slit along one side of the intestine and stomach, and wash out its contents. (What was the diet* of your particular specimen?) Notice the two portions of the muscular stomach, the lining of the longer limb of the 'J' being folded longitudinally, while the shorter limb is smooth. Notice the large sheet of membrane rolled up inside the intestine, serving to increase the absorbing area and also to stop food from passing down the intestine too quickly. Identify the *gall-bladder*, a thin-walled sac embedded in the anterior part of the right half of the liver.

(v) Remove the food-canal by cutting across the anterior end of the stomach and across the hinder part of the intestine anterior to the cloaca. Also remove the liver. In the female fish, identify the female reproductive organs, consisting of a pair of *ovaries* near the base of the liver and a pair of *oviducts* extending the full length of the body-cavity and joining together at their posterior ends to form the *vagina*, which opens into the cloaca.

(N.B.—There is no direct connection between the ovaries and the oviducts. In Scoliodon each ovary is attached to a long, thick tube—the epigonal organ†—which you must be careful not to mistake for an oviduct.)

The posterior portion of each oviduct forms a wider tube, a *womb*† (or *uterus*†) in which the fertilized egg-cells develop. In the breeding season, developing embryos may be found in dissected female specimens. In Scoliodon these embryos are retained in the womb until they are several inches long at birth. (Make a drawing to show as much of the internal organs as possible.)

In the male fish, the two *testes* are long and narrow, extending

the greater part of the length of the body-cavity. Leading backwards from the anterior end of each testis, the much-coiled sperm-ducts overlie the anterior portion of each kidney and finally open into the cloaca.

Remove the reproductive organs and expose the fully-developed posterior portion of the two kidneys, i.e. the portion concerned with excretion.

(vi) Expose the heart-cavity by carefully slicing away the ventral portion of the shoulder-girdle. The part of the heart you see from the ventral surface is the thick-walled, conical *ventricle*. If this is pushed to one side, the large, thin-walled *auricle* can be seen, occupying the dorsal half of the heart-cavity.

Cut through the jaw and through the gills on one side, and turn the floor of the mouth outwards. Examine the gills.

THE GUINEA-PIG

We have already dissected two *vertebrate* animals—a *frog* and a *fish*. We shall now examine another Vertebrate, the guinea-pig, as an example of the highest class of animals—the *mammals*—the class to which Man himself belongs. We select the guinea-pig because it is easily obtained and is conveniently dissected. A rabbit or rat or kitten can be dissected in the same way.

EXTERNAL CHARACTERISTICS OF THE GUINEA-PIG

(I) Watch the movements and examine the external characters of living mammals, e.g. cats, dogs, rats, mice, rabbits, or guinea-pigs. The animal is *sensitive* and *responds* quickly to a *stimulus*. Notice the movable external ears, the wide range of vision, the whiskers† and eyebrows† (which are organs of touch). Watch the animal feeding and notice that the lower jaw is freely hinged and can move up and down; in gnawing mammals, like the rabbit and guinea-pig, the lower jaw can also be moved slightly from side to side and from back to front.

(II) Examine a guinea-pig that has been freshly killed with chloroform. Notice (i) that the body is covered with *hair* and (ii)

that the body is divided into distinct body-regions—*head*, *neck* and *trunk*. (The neck is more clearly marked in many other mammals.)

Examine the *head* and notice (*a*) the *mouth*, with a pair of soft lips, the upper lip being slit down the middle, connecting the mouth with the *nostrils* and exposing the sharp-edged gnawing teeth (or *incisors*).† Inside the mouth notice that the teeth are fixed in sockets in the jaw-bone and that they are of two main kinds; gnawing teeth (*incisors*) and grinding teeth—*molars*† and *pre-molars*.† The roof of the mouth in front is hard and ridged (the *hard palate*)†, the ridges helping to retain food in the mouth while chewing, while at the back of the mouth the roof is soft (the *soft palate*)†. Notice also (*a*) the muscular *tongue*, attached at its root to the floor of the mouth and free and movable in front, (*b*) the *epiglottis*, a stiff flap lying just behind the tongue and covering the *glottis* at the entrance to the wind-pipe, (*c*) the whiskers and eye-brows (sense-organs of touch), (*d*) the *external ears*, (*e*) the *eyes* and *eyelids*, (*f*) the *trunk*, consisting of the chest (or *thorax*), strengthened by the ribs and breastbone on its ventral side, and the belly (or *abdomen*) with a muscular body-wall on its ventral side.

In both sexes, the combined *excretory and reproductive duct* opens in front of the *anus*. In the *male* animal, this opening is at the end of the *penis*, and on either side of the penis is a *sac* containing a *testis* that produces sperms. In the *female* animal, there is a slit-like opening. The ventral surface of the female animal also bears several pairs of *milk-glands* with milk-ducts opening at *teats*.†

DISSECTION OF THE GUINEA-PIG

Place the animal on its back on a dissecting-board, tying the limbs to hooks in the four corners of the board so as to stretch out the body. Wet the fur along the mid-central line.

(i) Pinch up the *skin* in the middle of the belly-surface and make a cut (*through the skin only*) with the scissors. Continue this cut forwards along the middle line to the neck, backwards to near the reproductive opening, and along the upper part of the limbs. With a sharp knife, separate the skin from the underlying muscular body-

wall, and pin it out on each side. (While removing the skin, notice the *milk-glands* in the female and the *scrotal*† *sacs* in the male.)

(ii) Pinch up the muscular *body-wall* in the middle of the belly-surface and cut through it along the mid-ventral line, forwards to the gristly end of the breastbone, and backwards to near the reproductive opening, being careful not to injure any internal organs. Make transverse cuts just behind the ribs and across the hinder part of the belly-wall and then pin back the body-wall on either side. Draw a plan of the internal organs of the belly-cavity as they lie, before disturbing them. Notice (*a*) the large, reddish-brown *liver*, (*b*) the light-coloured *stomach*, partly hidden by the liver, (*c*) the much-coiled *small intestine*, (*d*) the wide, dark-coloured *caecum*,† hiding most of the intestines, (*e*) the dark-coloured *colon*,† (*f*) the *rectum* containing round lumps of faeces, and (*g*) the *bladder*, containing urine.

(A male guinea-pig has a pair of long, translucent sperm-sacs—absent in rabbits.)

(The food-canal must be handled with great care while dissecting, especially the caecum; if it is pierced the contents will leak out and cover the dissection with digested food material.)

FOOD CANAL OF THE GUINEA-PIG

(iii) Having made a plan of the undisturbed internal organs, carefully turn the food canal over to the animal's left side and, without cutting or tearing anything, identify (*a*) the *liver*, hanging from (*b*) the *diaphragm*, (*c*) the *gall-bladder*, embedded in the liver, with (*d*) the *bile-duct* entering the small intestine where it leaves the stomach; (*e*) the *gullet* leading to (*f*) the *stomach*; (*g*) the *spleen*, a dark red body near the stomach (*N.B.* The spleen is not part of the food-canal); (*h*) the *pancreas*, spread out in the first loop of the small intestine, and (*i*) the *pancreatic duct*. Notice that the intestines are enclosed and supported by a delicate, transparent membrane (the *mesentery*) in which run blood-vessels, lymph-vessels, and nerves, supplying all parts of the intestines. Identify the *hepatic portal vein*† where it enters the liver, and ligature it in two places

about half an inch apart, i.e. tie a loop of thread lightly round the vein so as to prevent loss of blood when it is cut between the ligatures.

(iv) Carefully remove the food-canal as follows: (*a*) Cut across the ligatured portal vein *between the ligatures*, (*b*) ligature the gullet just above the stomach and cut through *above* the ligature, (*c*) ligature the hinder end of the large intestine and cut through *below* the ligature. Now start at the hinder end and free the food-canal, cutting carefully through the supporting mesentery near the intestine and being careful not to cut the caecum or damage any large blood-vessels. (If a vessel is cut by accident, ligature it immediately to stop bleeding.) Do not damage the membrane filling the first loop of the small intestine or you may not be able to examine the *pancreas* and the *pancreatic duct*. Spread out the food-canal on a board and make a drawing, labelling the *gullet*, *stomach*, *bile-duct*, *pancreas*, *pancreatic duct*, *small intestine*, *caecum*, *colon*, and *rectum*. (If the animal is to be kept until a later lesson, remove the skin as far as possible at this stage.)

OTHER ORGANS IN THE BODY-CAVITY

(v) After removing the food-canal, carefully ligature the *posterior main vein* where it branches to the liver, and remove the liver. Then examine the *diaphragm*, which separates the chest-cavity from the rest of the body-cavity, consisting of a fibrous central portion with muscles round its margin. Identify the *main artery* lying dorsal to the *posterior main vein* and notice how these main blood-vessels give off branches to the various organs and to the hind limbs. Identify the blood-vessels shown in Fig. 66. Notice the two *kidneys* with their *arteries* and *veins*, the *adrenal glands*, and the two *kidney-ducts* (or *ureters*),† thin, white tubes leading from the kidneys to the bladder.

REPRODUCTIVE ORGANS OF THE GUINEA-PIG

(vi) Examine the *male reproductive system*. Pull out the left *testis* from its sac and notice its oval shape with a mass of coiled tubes at

one end that later join up to form a single *sperm-duct*. This tube loops over the *kidney-duct* and joins the sperm-duct from the right testis, opening into the neck of the *bladder* and forming a common duct that runs through the *penis*, opening to the exterior at the combined excretory and reproductive opening. Find the line where the bones of the hip-girdle meet on the ventral side, and cut through the bone at this point with a knife or a strong pair of scissors. Separate the two halves of the hip-girdle, and dissect out the reproductive organs. Draw the male reproductive and excretory organs and label the parts.

In the *female* animal, notice the two small, oval *ovaries* near the kidneys, and the two *oviducts*. Each oviduct consists of a narrow, wavy duct leading to a wider, thick-walled *womb* (or *uterus*), where fertilization takes place when a sperm meets a descending egg-cell and where the embryo develops. Both right and left oviducts enter the bladder and join to form the *vagina*, a common duct by which the excretory and reproductive systems open to the exterior. Draw the female reproductive and excretory organs and label the parts.

ORGANS OF THE CHEST-CAVITY AND THE NECK

Notice that the exposed surface of the diaphragm is concave. Then make small cuts between the lower ribs on either side of the breastbone and notice how the diaphragm flattens out as the air enters the chest-cavity between the ribs and the lungs. Cut carefully through the ribs (except the first) on either side of the breastbone. Then cut across the breastbone and remove it. Through the opening, identify and sketch the position of (*a*) the *heart*, enclosed in a thin double-walled *heart-sac*, (*b*) the right and left *lungs* in their *pleural cavities*. Notice, too, the *muscles* between the ribs. Now cut through the ribs on either side, as near the backbone as possible, cutting *carefully* through the first rib on either side. Remove the heart-sac *very carefully*, so as to expose the main blood-vessels entering and leaving the heart. Now cut through the body-wall of the neck along the mid-ventral line and expose the underlying structures.

Identify (*a*) the thin-walled right and left *auricles*, (*b*) the thick-walled right and left *ventricles*, (*c*) the *pulmonary artery leading from the right ventricle to the lungs*, (*d*) the thick-walled *main artery* (or *aorta*) arising from the left ventricle, bending over to the left behind the heart and passing through the diaphragm into the belly-cavity as the *dorsal artery*. Notice the branches given off by the main artery: (*e*) the right and left *arteries to the fore-limbs*, and (*f*) the right and left *arteries to the head*. Identify the thin-walled right and left *anterior main veins* (or *superior venae cavae*)† receiving blood from (*g*) the right and left *veins from the head* and (*h*) the right and left *veins from the fore-limbs*. Identify, also, the thin-walled *posterior main vein* (or *inferior vena cava*) returning blood to the right auricle from all parts of the body behind the diaphragm, and also the *pulmonary veins returning blood from the lungs to the left auricle*. Draw separate diagrams of (i) the arteries, and (ii) the veins, labelling the blood-vessels.

Notice the ringed *windpipe* ventral to the *gullet*, with the *voice-box* at its anterior end.

The upper end of the wind-pipe opens into the mouth by the *glottis*, protected by a stiffened flap, the *epiglottis*. Cut across the wind-pipe and tie into it a blowpipe (or the expanded end of a glass tube). Blow into the tube and watch the lungs expand.

Remove the skin from one side of the head and notice the *salivary glands*. There are four pairs of these in the rabbit and guinea-pig, two pairs behind or between the angles of the jaws, one pair under the tongue and one pair below the eye-sockets.

Notice what a large *nerve* looks like, e.g. the one supplying the fore-limb and running near the blood-vessel to the fore-limb.

Examine the large *muscle* of one of the limbs and notice how it is attached to the bones by *tendons* at either end.

Carefully remove the bones forming the dorsal surface of the skull so as to expose the *brain*. Identify the *big brain* consisting of two halves (the *cerebral hemispheres*), and also the *little brain* (the *cerebellum*).

Examine a prepared skeleton.

GLOSSARY

(Simple definitions of general-purpose words in the text that are not included in the standard vocabulary on which the Course is based and which were not used in Books I and II.)

absolute, not relative or comparative, but real and unqualified, 27
acquire, gain by oneself or for oneself, 149
adult (*adj*. and *n*.), grown-up (person), 103
alloy (*n*.), mixture or compound of two or more metals, 260
ancestor, any of those from whom one's father or mother is descended, 138
ankle, joint connecting foot with lower leg, 103
apex, highest point, top, 249
apparent, seeming, but not true (opp. real), 22
approach (*v*.), come near(er), 286
aquarium, water tank for live *aquatic* animals, 147
aquatic, living in or near water, 91
arc, part of a circle, 130
arch (*n*.), curved structure supporting bridge, floor, etc., 123
asexual, non-*sexual*, reproduction without sex-cells (opp. *sexual*), 144
astronomer, person skilled in *astronomy*, the science of the stars and other heavenly bodies, 197
atlas, (here) book of maps, 266
axis, line dividing anything into two *symmetrical* parts exactly similar in shape and size; imaginary line about which anything *rotates*; bar (axle) on which a wheel turns, 120

bi-metallic, consisting of two metals, 17
bounce, rebound suddenly, like a rubber ball springing up again after striking the ground, 104
bristle (*n*.), short stiff hair, 150
brittle, easily broken when bent, not *flexible* or elastic, 120
bullet, metal shot fired from *rifle*, 73

calf (here), young of cow, 88
calibre, internal diameter; bore (*n*.) of tube, 125
capacity, holding-power, receiving-power, 3
cast-iron, impure, *brittle* form of iron; *pig-iron*, 14
cast off, throw(n) off, let fall from, 153
caterpillar, soft-bodied, worm-like first stage (after egg) of certain insects (e.g. butterflies and moths), 135

chew, bite up (food) until soft, 93
circuit, roundabout journey ending where it began, 173
claw, pointed nail of bird's or beast's toe, 155
clockwise, *rotating* in same direction as hands of clock, 273
clot (*v.*), form into half-solid lump or *clot* (*n.*) (of blood, milk, etc.), 105
coincide, occupy the same space; happen at the same time, 205
collapse (*v.*), fall down or fall in, 97
comma, punctuation mark (,), 162
community, group (of men, insects, etc.) living in same place or *environment*, 143
compact (*adj.*), closely packed; tightly packed, 90
compartment, a separate part divided off, 102
compass, (here) *hinged* instrument for drawing circles, 195
compensated, (here) provided with a device for neutralizing the effect of temperature, 18
concentric, having the same centre, 72
confine, keep within limits, 169
conserve, preserve without increase or decrease, 75
construct, (here) draw; fit together; build, 208
converge, come together from different directions to meet in a point (opp. *diverge*), 145
convey, carry, 29
core, central part, 272
crank, part of axle bent at right-angles for converting straight up-and-down movement into circular or *rotary* movement, 80, Fig. 49
create, make; bring into existence, 75
critical, (here) marking sudden change-over from one physical state or condition to another, 221

deficit, shortage (opp. excess or *surplus*), 66
deflect, turn aside, bend away, 72
deviate, turn aside; also *n.*, *deviation*, (here) *deflection* of compass-needle by local attraction, 269
diet, choice of food; kind of food on which person lives, 298
diminish, make less, become less, 106
distribute, share out, spread out, also *n.*, *distribution*, 138
diverge, spread out from a point in different directions (opp. *converge*), 206
dominant, (here) occupying commanding position, 87
down (*n.*), first covering of young birds, small soft under-feathers, 186
dramatic, striking, exciting, 72
duct, tube or pipe that conducts fluid, 116
duster, cloth for dusting furniture, etc., 59

embed, fix firmly in surrounding material, 31
emerge, come out into view, 163
ensure, make certain, make safe, 255
environment, the conditions in which an organism lives (e.g. temperature, light, water, other neighbouring organisms), 90
evolve, develop by natural process, also *n. evolution*, 137

fin, swimming and steering *organ* of fish, 120
fist, the hand when tightly closed, 102
flap (*n.*), thin *hinged* sheet, 93
flexible, easily bent without breaking (opp. *brittle*), 120
foil (*n.*), metal hammered or rolled into very thin sheet, 39
fore, in front; front part (opp. *hind*), 89
fundamental, forming a foundation, essential, 92

gape, beak-opening, widely opened mouth, 281
generation, all individuals born about the same time; average time in which offspring are ready to replace parents (about 30 years in Man), 91
giant, unusually big person, animal or plant (opp. *dwarf*), 166
gnaw, bite repeatedly with front teeth, as does a mouse or rat, 120
grasp (*v.*), seize and hold firmly, also *n.*, 88
grip (*v.*), *grasp* tightly, also *n.*, 16

hatch (out), *emerge* from egg, 154
helmet, protective head-cover, 39
herb, (in strictly botanical sense) soft non-woody flowering plant whose shoot dies down every year (as distinct from woody-stemmed trees and shrubs); also *adj. herbaceous*, 145
hermaphrodite (*adj.*), possessing both male and female reproductive organs; *bi-sexual*, 295
hind (*adj.*), situated at the rear or tail end of an animal (opp. *fore*), 89
hinge (*v.* and *n.*), (attach with) movable joint, 120
honey, sugary liquid made by bees and stored in cells of *honey-comb*, 117
horn, *outgrowth* on heads of cattle, etc.; any outgrowth of similar shape (e.g. on snails), 167; *horny* (*adj.*), hard and tough like cow-horn, 126
hypotenuse, the side opposite the right angle (i.e. the longest side) in a right-angled triangle, 222

illuminate, light up, 229
image, (here) likeness of an object's external form produced by a mirror or lens, 200
impulse, force or stimulus acting for a short time; a quick blow or push, 128
indicator, something that *indicates*, points out, shows, 7; *indication*, sign, suggestion, 67

induce, produce magnetic or electrical condition by *induction* with neighbouring magnetized or electrified body, 260
infect, give disease to, convey *infection*, 111
inflammable, easily set on fire, 81
inject, force (fluid) into a closed space; *injector* (*n.*), instrument for *injecting* (e.g. water into boiler of steam engine; oil into cylinder of Diesel engine), 82, Fig. 53
injure, do harm to; (*n.*) *injury*, 85
insulate, cut off from outside influence (usually from heat exchange or electrical effects), *isolate*; (*n.*), *insulation*, 13
intelligent, able to learn by experience, able to understand; (*n.*), *intelligence*, 133
interlock, hold together by means of projections fitting into corresponding openings, 185
intersect, cross or cut each other, 209
involuntary, not controlled by the will (opp. *voluntary*), 94
irritable, (here) able to respond to a stimulus, 135
isolate, place apart or alone; cut off from outside influence, 262

jacket, outer covering, 35
jam, fruit preserved by boiling with sugar, 141

keel, lowest longitudinal beam of ship on which ship's framework is built up, 172
kitten, young cat, 88

labour, work, pieces of heavy work, 118
lantern, transparent case enclosing source of light, 230
latent, existing in an inactive state or condition, 58
ligature (*n.*), a tightly tied bandage or thread; also (*v.*), 282
longitude, angular distance east or west from the *meridian* of Greenwich, 21

major (*adj.*), of the greater, more important, kind (opp. *minor*), 118
marine (*adj.*), of, from, beside, the sea, 141
membrane, thin *flexible* sheet of *tissue* covering or connecting parts of body, 92
meridian, imaginary line on Earth's surface passing through North Pole, South Pole, and round again to North Pole, 256
meteorologist, person skilled in *meteorology*, the science of the weather, 69
migrate, (here) move from one place to another as the season changes, 184
minimum, least possible quantity or size (opp. *maximum*), 8
minor (*adj.*), of the smaller, less important, kind (opp. *major*), 118

modify, make partial changes in, 131
motor (*adj.*), designed to move or cause movement, 129

nodule, small swelling, 140
nut, (here) small block of metal with internal screw-thread to fit on rod (or *bolt*) with external screw-thread, 19

obliquely, in a sloping position or direction; inclined at an angle other than a right-angle, 185
optical, relating to *optics*, the scientific study of light, 210
organ, part of a living organism that carries out some special function (e.g. a *sense-organ* responds to an external stimulus), 2
outgrowth, that which grows out of or from anything, 155
oval, more or less egg-shaped, 167

paralysed, unable to feel or move owing to failure of nerve-action, 148
partial, incomplete (opp. *total*), 72
patient (*n.*), sick person under a doctor's care, 10
period, any length of time, 7
perpendicular, a line at right-angles to another line or plane, 200
physiologist, person skilled in *physiology*, the study of how organisms work, 69
pierce (of sharp-pointed instruments), go into or through; make a hole by doing this, 161
pig-iron, crude iron, *cast iron*, 273
pivot, short pin or centre on which something swings or turns, 256
plane, flat surface, 201
planet, a heavenly body that revolves round the Sun, 197
plasticine, a plastic non-drying material resembling damp clay, 195
plot, (here) mark point on graph; draw a plan or graph, 11
polarity, arrangement of opposite magnetic poles, 259
pouch, a bag or pocket; (here) bag-like *receptacle* containing mammary glands, into which new-born animals are placed, 138
prey, animal hunted and killed by flesh-eating animal for food, 186
produce, (here) extend straight line in same direction, 200
project (*v.*), stand out beyond the rest of the surface or edge; throw pictures on to a screen, 89, 230
prominent, sticking out, standing out distinctly, 124
protractor, instrument for *plotting* or measuring angles, 200

receptacle, a containing vessel, place, or space, 288
reel, cylinder for holding wound cotton thread, 213
relax, allow to become loose or less stiff, 94

repel, push away, drive (something) back, 257
resemble, be like, have same appearance as, 139
rifle, (hand-gun with) spiral groove inside barrel for *rotating* the *bullet*, 73
rotate, turn round and round, revolve, 246

sac, bag-like part or organ, 96
saddle, rider's seat placed across back of horse, etc.; anything of that shape, 150
safeguard (*n.*), protection, 98
scrap, small separate piece; odds and ends or leavings (e.g. *scrap-iron*), 273
screen, (here) sheet of cloth, paper, etc., on to which pictures or shadows are *projected*, 195
seeker, (here) blunt-ended dissecting-needle for passing into ducts, etc., 287
segment, part of a circle cut off by a straight line, 21; one of the ring-shaped body-divisions of a jointed animal (e.g. worm, insect), 149
semicircular, shaped like a half-circle, 220
sense-organ, *organ* for feeling, seeing, hearing, tasting, smelling, etc., 2
sensory, of the senses, 129
sexual, (reproduction) involving union of sex-cells, 144
similar triangles, triangles of the same shape but of different size, 232
sine (of an angle), length of side opposite to the angle divided by length of *hypotenuse*, 220
skip, jump lightly up and down using a skipping-rope, 104
slipper, loose indoor shoe, 146
social, concerned with living in societies or *communities*, 166
socket, hollow for something to fit into or turn in, 88
spoke, (here) radial rod or wire connecting centre of wheel with its circumference, 12
spongy, elastic, porous, and absorbent as a *sponge* used for bathing the body, 96
sprinkle, scatter small drops or particles, 262
squeeze, apply pressure to, 105
sterilize, make *sterile*, i.e. free from living micro-organisms, 86
stream-lined, shaped so as to offer *minimum* resistance to movement through a fluid, 296
substitute, put in place of, exchange for, replace by, 103
sustain, keep going continuously, maintain strength, 125
swamp, (*n*), wet *spongy* ground, 106
switch (*v.*), turn (electricity, etc.) on or off; also *n.*, 250
symmetrical, the same on both sides, divisible into two or more parts of exactly the same shape and size (opp. *asymmetrical*); (*n.*), *symmetry*, 148

tangent (to a curve), straight line touching the curve at one point, 209

tape, narrow woven strip of cloth, 20
telescope, *optical* instrument for viewing distant objects, 156
temple, (here) flattened region on either side of human forehead (i.e. between the top of the ear and the eye), 103
thermal, of heat, 16
timber, wood that can be used for building, 142
tissue, a mass of cells all of the same kind and function, 110
translucent, transmitting light but not transparent, 168
trigonometry, the mathematics of triangles, 220
trunk, (here) mammal's body without head, neck, limbs and tail, 89
tumult, violent disturbance, (*adj.*), *tumultuous*, 72

venous, of the veins, 105
verify, show to be true (by experiment), 210
vinegar, sour (acid) liquid got from alcohol and used for flavouring and preserving food, 140
virtual, seeming, *apparent* (opp. *real*), 208
voluntary, controlled by the will (opp. *involuntary*), 124

web, (here) *membrane* connecting toes, 178
whirl, spin round and round (like water in a *whirlpool*), 280
withstand, hold out against, resist, 18

yolk, store of food material in eggs of most animals, 92

INDEX

WHERE there is more than one page-reference to the same subject, the principal reference is printed in heavier type. The dagger-sign (†) in front of a word shows that this is a technical term that has not been used before in Books I and II, and which is not explained in the Glossary. These new technical terms and scientific words are also marked (†) where they first appear in the text, and where their meaning is explained.